TURBULENCE SCALES IN THE PASSAGE OF A LINEAR TURBINE CASCADE

THESIS

James L. Acree, Captain, USAF

AFIT/GAE/ENY/90D-1

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

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Wright-Patterson Air Force Base, Ohio

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James L. Acree, B.M.E., M.S.E.

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I am grateful to God for providing me with a loving wife, Rhonda, and three children, who have seen me through two graduate programs.

In Memoriam

Wayne Wilsdon

Captain, USAF

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Symbol	Definition
Roman Symbols	
a_1, a_2 b_1, b_2 c_1, c_2	Hot wire velocity calibration coefficients
b	Jet grid tube diameter (mm)
$\vec{b}$	Vector of hot wire velocity calibration coefficients for wire 1
$\overrightarrow{b1}$	Vector of hot wire velocity calibration coefficients for wire 2
c	Blade chord (mm)
$\dot{e}$	Turbulent kinetic energy dissipation rate (W/kg)
h	Convection heat transfer coefficient (W/m^2 °K)
k_1, k_2	Hot wire angle calibration coefficients
k	Thermal conductivity (W/m °K)
l	Distance along the streamline through the cascade passage (mm)
n	Frequency (Hz)
q	Dynamic pressure (kPa)
s	Distance along the blade surface from the leading edge (mm)
t	Time (s)
u	Flow velocity component parallel to the probe bisector, approximating the streamline (m/s)
v	Flow velocity component perpendicular to the probe bisector, approximating the horizontal component normal to the streamline (m/s)

x	Distance along the blade chordline (mm)
A	Area (m^2)
C_p	Pressure coefficient on the blade surface
E_1	Measured bridge voltage from hot wire 1 (volt)
E_2	Measured bridge voltage from hot wire 2 (volt)
ERR	Mean squared error between computed and measured values
$E(n)$	Spectral turbulent energy distribution function
$H(u')$	Contribution to $\overline{u'^2}$ from the Fourier transform of u' (m^2/s^2)
I	Electrical current (ampere)
N	Total number of discrete values
Nu	Nusselt number
P	Pressure (kPa)
Pr	Prandtl number
R	Radius (mm)
R''	Electrical resistance per unit area of the foil
Re	Reynolds number
SSE	Sum of squares of errors
St	Stanton number
Tu	Turbulence intensity in percent
U_{1eff}	Effective air velocity measured by hot wire 1 (m/s)
U_{2eff}	Effective air velocity measured by hot wire 2 (m/s)
U_∞	Freestream air velocity (m/s)
W	Matrix of hot wire velocity quadratic fit terms

Greek Symbols

α	Probe bisector angle from index arm 2
β	Flow angle with respect to probe bisector, during flow measurement; angle from index arm 1 to index arm 2
γ	Angle to index arm 1 from test section Y axis
ϵ	Surface heat radiation emmissivity

θ	Flow angle with respect to probe bisector, during probe calibration
λ	Turbulence microscale length (m)
μ	Dynamic viscosity coefficient (kg/m s); angle between hot wire sensors
ν	Kinematic viscosity (m^2/s^2)
ρ	Fluid density (kg/m^3); electrical resistivity (ohm - cm)
σ	Flow angle discriminant value
ψ	Flow angle from the test section X axis
ψ_L	Angle from the test section X axis to the probe bisector
Λ	Turbulence integral scale length (m)

Subscripts

∞	Free stream condition, prior to cascade entry
c	Blade chord is the reference length
eff	Effective
p	Pressure
rms	Square root of the mean of the squares
s	Surface distance from tap 1 is the reference length
u	Tangent to the average streamline
v	Normal to the average streamline
x	Surface distance from the leading edge is the reference length
R	Based on radius of curvature

Superscripts

'	Fluctuating component
$\overline{}$	Mean value

Abstract

Convective heat transfer in a turbine cascade is examined for turbulence effects. Turbulence in the free stream is varied by injection of air through a jet-grid device upstream of the cascade. Pressure and flow patterns on the blade surface, and flow velocity in two components, are examined to determine the effect of the jet-grid. Velocity and velocity fluctuation in two components are measured. Local turbulence scales through the cascade passage are determined, and local turbulent energy dissipation rate is determined.

Results indicate that injection of air through the jet-grid changes the angle of incidence, and therefore changes the surface pressures and velocities on the blade. Heat transfer comparison is thereby invalidated. Variations in jet-grid plenum pressure change the turbulence microscale at the cascade entrance, but not the integral scale. Turbulence intensity is likewise relatively unaffected.

Turbulence behavior in the passage indicates that velocity fluctuation and turbulence microscale are inversely related; turbulence intensity and microscale are not inversely related. With 6% freestream turbulence intensity, turbulence in the passage center is influenced first by events near the suction surface, then by events near the pressure surface. The primary vehicle for cross-stream diffusion is increased cross-stream velocity component fluctuations.

TURBULENCE SCALES
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I. Introduction

Is it by your understanding that the hawk soars,
stretching his wings toward the south?
Is it at your command that the eagle mounts up,
and makes his nest on high?
- Job

1.1 General

Part of the Integrated High Performance Turbine Engine Technology Initiative (IHPTET) is the pursuit of increases in turbine efficiency. Part of this increase must come from a reduction of turbine cooling air, even though the turbine inlet temperatures will be increased to near- stoichiometric conditions (i.e., approaching 4000 F). This calls for more accurate methods for scheduling the cooling air flow rate based on the heat transfer actually occurring in the first stage turbine blades. Too little cooling air allows thermal damage to accumulate; too much leads to thermal shock damage when the throttle is opened, and generally wastes energy.

The flow entering these devices is characterized by high turbulence, induced in the combustor to accelerate combustion and to provide a near-uniform temperature distribution in the flow entering the nozzle. This high temperature air is accelerated through the nozzle, where low-temperature air is added for film cooling. Here the turbulent flow experiences acceleration and shearing that change the nature of the turbulence. Turbulence is also generated by the interaction of the boundary layers with the nozzle vanes and turbine blades, and by the turning of the flow in general. From the rotating turbine blade perspective, high-speed, low-turbulence, high-temperature jets from the nozzle passages alternate with low-speed, high-turbulence, low-temperature wakes from the nozzle vanes. Thus, turbulence is increasing and decaying in different modes and rates at various locations in the flow passages, and all of this happens in cyclic waves ("unsteadiness").

The turbulence levels entering the turbine are known to exceed 20 percent. It has been shown (MacMullin et al., 1989) that free stream turbulence levels above 7 percent cause an increase in the heat transfer rate in an already turbulent boundary layer. The increase is dependent on configuration, but can exceed 75 percent for a flat plate.

Measurement of the turbulence parameters and prediction of their change in the turbine passages, coupled with knowledge of how these parameters are related to heat transfer from the flow to the device,

provides a basis for scheduling the cooling air flow rate to accomodate the changing heat flux. In 1989, low speed studies of heat transfer and turbulence in turbines were begun at the Air Force Institute of Technology (AFIT) at Wright-Patterson AFB, Ohio. A linear turbine cascade wind tunnel was assembled and fitted with four turbine blades of high-work design. The two inner blades were instrumented: one for static pressure, one for heat transfer. A high speed data acquisition system was assembled to take time-discrete data from a two-sensor hot wire anemometer. Software was written to drive the data acquisition system, then to reduce the voltages to velocities and finally to turbulence parameters.

The initial study (Galassi, 1989) incorporated a broad look at a turbulence generating device. A row of parallel tubes was inserted into the flow upstream of the turbine cascade. These tubes were pierced by orifices which emitted parallel jets of air. The orientation of the jets, the orifice diameters, and the pressure of the air supplied to them, were varied to examine the effect of each on two turbulence parameters and on heat transfer occurring on the #2 blade surface.

This study is an extension of the 1989 analysis. Several questions were raised in the initial study that invited further investigation. It appeared that the turbulence intensity and integral scale could be held fixed while the microscale was varied by using a cross-flow jet grid, and changing the secondary flow pressure. The

influence of the microscale parameter on heat transfer parameters might be isolated from the integral scale effects. The present effort was focused directly on this goal.

Generally speaking, the microscale is related to the size of the smallest parcels of fluid in which all particles share the same velocity. Increasing turbulence intensity brings a decrease in the microscale; smaller fluid parcels possessing increased kinetic energy. The small, more energetic parcels may be better able to penetrate the boundary layer on the blade surface, bringing cooler freestream fluid into contact with the heated blade surface.

A note on terminology is in order. *Primary flow* refers to the air entering the tunnel bell mouth and proceeding through the tunnel. *Secondary flow* refers to the air forcibly injected into the primary flow, upstream of the cascade, in order to vary the free stream turbulence levels. Horseshoe vortices and other non-2D type air movement is collectively referred to as *passage vorticity*. *Normal* denotes components perpendicular to the local current streamline.

Units used in the body of this document are SI; however, the appendices contain English units, as these are more practical for the details of the apparatus, as it was built to English unit specifications.

1.2 Objectives

1) Measure pressure distributions on the turbine blade surface at various levels of jet grid plenum pressure. Derive Reynolds numbers and local velocity. Identify flow separation points and end wall vor-

tex zones on the blade.

2) Measure temperature distribution on the blade surface while the surface is artificially heated. Derive heat transfer information in the form of Nusselt and Stanton numbers, for various flow conditions.

3) Measure velocity fluctuations with time, at various locations in the cascade and at various flow conditions. Derive turbulence parameters, and compare to previous models of turbulence decay. Identify regions of strong turbulence production.

4) Determine the relationship between free stream turbulence parameters and heat transfer parameters for the blade surface. Examine turbulence decay through the cascade. Identify the effect of the jet-grid on the cascade flow and the heat transfer parameters.

1.3 *Method*

A blade (No. 2) was constructed with an electrically heated surface foil. Thermocouples were fixed to the inside of the foil, and mounted in the blade interior. Pressure taps were built into a section alongside the foil. The test section end-walls were modified to permit placement of a probe or Pitot-static tube anywhere in the cascade.

The primary flow characteristics of the Moore and Galassi studies were reproduced in terms of blade profile and flow turning angle. All jet grid parameters, except plenum pressure and temperature, were fixed. The primary flow speed was held approximately constant.

Pressure transducers were calibrated, and the hot wire anemome-

ter was calibrated for various tunnel stagnation temperatures. The foil resistance was measured.

Flow visualization experiments using oil drops were completed to identify flow separation points and regions of strong passageway vorticity. Photographs recorded the flow patterns for flow with and without the grid installed.

The secondary flow plenum pressure was controlled so as to vary the subsonic injection speed at the jet grid orifices of an eight-tube grid. Blade surface pressure and thermal data were measured for different plenum pressure levels. Freestream velocity and velocity fluctuations were measured via hot wire at the cascade inlet (location C). Velocity profiles across the cascade entrance were measured with a pitot-static tube.

With secondary flow fixed (20 psi plenum pressure, ten-tube grid), the hot wire probe was used to measure turbulence parameters at 15 locations in the cascade passage. Blade surface pressure and heat transfer were also measured.

II. Theory

2.1 Heat Transfer

Two primary heat transfer parameters were used in this study to describe the ability of the flow to absorb heat from the foil. These are the local Nusselt number (Nu_x) and the local Stanton number (St_x). These dimensionless parameters are defined as

$$Nu_x = \frac{h \cdot x}{k}$$

and

$$St_x = \frac{h}{\rho \cdot V \cdot C_p}$$

where h is the local convective heat transfer coefficient

x is the distance along the surface from the leading edge

k is the thermal conductivity of air

ρ is the air density

V is the local flow speed

C_p is the heat capacity of air at constant pressure

For flow normal to a rounded-nose blunt body, heat transfer near the stagnation point (in two-dimensional laminar flow) is modeled using the radius of curvature R as the length scale of the Reynolds number (Kays,1980);

$$Nu_R = 0.81 \cdot Re_R^{1/2} Pr^{0.4} \tag{2.1}$$

This relation is considered valid for $x/R \ll 1$. Taps 1 and 2 (Figure 2.1) fulfill this criteria. For other locations on the heated surface, the value of h is determined via a steady state heat flux equation that ignores heat conduction through the thin edges of the foil. Details appear in appendix B.

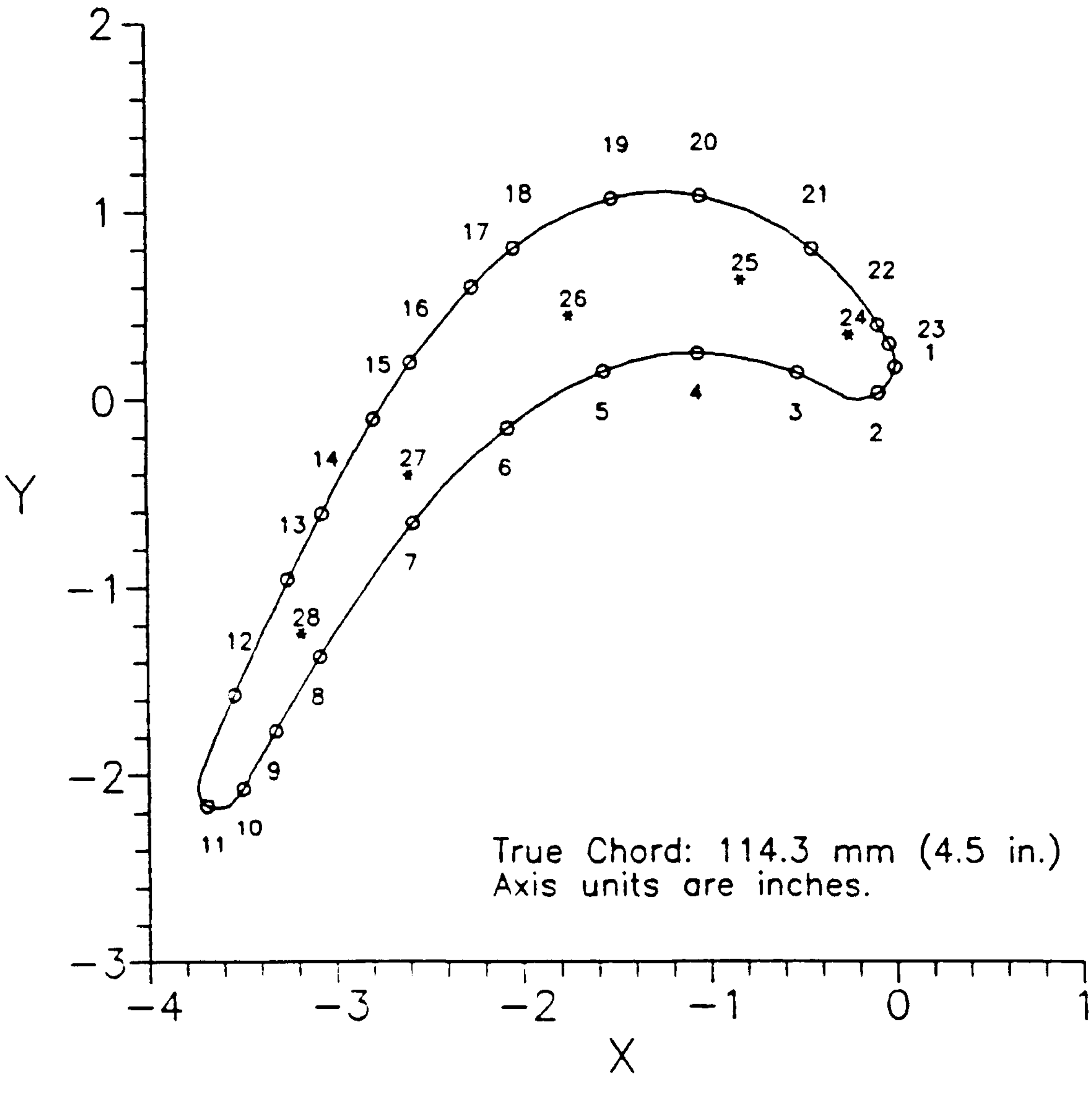


Figure 2.1 Thermocouple Locations On Blade 2

2.2 Turbulence

The transition from laminar to turbulent boundary layer flow is reflected directly by a significant increase in convective heat transfer. This phenomena is well documented. What is not clear is how free stream turbulence influences an already turbulent boundary layer in terms of heat transfer. Intuitively, it appears that higher turbulence in the free stream should propagate into the boundary layer, to improve the ability of small parcels of cooler free stream fluid to penetrate the boundary layer and contact the heated surface. This is confirmed by experimental data (MacMullin et al., 1988).

Turbulent flow can be analyzed in terms of a steady-state velocity and a fluctuating velocity for any reference axis. In the streamwise direction, for example, the instantaneous velocity component u is considered in two parts:

$$u = \bar{u} + u'$$

Turbulence is a characteristic of a flow, and can be described by three readily evaluated parameters: the turbulence intensity, the turbulence integral scale, and the turbulence microscale. Turbulence intensity in two dimensions is composed of root-mean-square values of the fluctuating velocity components of u and v:

$$Tu = \sqrt{\frac{Tu_x^2 + Tu_y^2}{2}} \cdot 100\% \qquad (2.2)$$

where

$$Tu_x = \sqrt{\frac{\sum_{i=1}^{N}(u')^2}{N}} \quad ; \quad Tu_y = \sqrt{\frac{\sum_{i=1}^{N}(v')^2}{N}} \tag{2.3}$$

When generated, turbulent flow is generally *anisotropic*, meaning that it shows strong directionality (and therefore has structure). In time, the turbulent action breaks down any directional preference, and it approaches *isotropic* turbulence, where no directionality is detectable.

2.2.1 Integral Scale and Microscale Lengths

Two lengths (scales) associated with turbulence are useful in describing the nature of turbulent flow. The integral scale Λ is related to the size of large turbulent eddies, such as eddies in a Karmann vortex street. The microscale length λ is a theoretical measure of the smallest measurable homogeneous group of fluid, such that all particles in the group have the same velocity. The turbulence scale parameters are functions of the frequency distribution of the fluctuating velocity components. Decreasing microscale, for example, means higher frequencies are present in the velocity fluctuations.

The amplitudes and frequencies that comprise the fluctuating component are measurable, and are related to the turbulence scale lengths by the spectral distribution function across a frequency bandwidth. This relationship is developed by Hinze (Hinze, 1959).

Let $E_{u'}(n)$ denote this distribution function, where n is the frequency variable. Then the spectral energy distribution is related to the fluctuating velocity component as

$$\overline{u'^2} = \int_0^\infty E_{u'}(n)dn \tag{2.4}$$

One can obtain $E_{u'}(n)$ from the Fourier transform of the discrete u'^2 data by employing Parseval's theorem for a discrete function:

$$\sum_{k=0}^{N-1} u'^2 = \frac{1}{N}\sum_{n=0}^{N-1}[H(u')]^2 \tag{2.5}$$

where $H(u')$ is the spectral function of u' from the Fourier transform of u'.

This can be rearranged to give

$$\frac{1}{N}\sum_{k=0}^{N-1} u'^2 = \frac{1}{N^2}\sum_{n=0}^{N-1}[H(u')]^2 \tag{2.6}$$

or

$$u'^2_{rms} = \sum_{n=0}^{N-1}\left[\frac{H(u')}{N}\right]^2 \tag{2.7}$$

Comparing the integrand of (2.4) to the term being summed in (2.7) it is seen that $E_{u'}(n)$ is related to $H(u')$ such that (Equation 1-90, Hinze)

$$E_{u'}(n) = \left[\frac{H(u')}{N}\right]^2 \frac{1}{dn} \tag{2.8}$$

If it is true that $\bar{u} \gg u'$, then time t can be replaced (Taylor's hypothesis) by

$$t = \frac{x}{\bar{u}} \tag{2.9}$$

From Fourier transform theory, a *longitudinal correlation function* $f(x)$ is related to the *spectral power density* $E_{u'}(n)$ as

$$f(x) = \frac{1}{\overline{u'^2}} \int_0^\infty E_{u'}(n)\cos\left(\frac{2\pi n x}{\bar{u}}\right)dn \tag{2.10}$$

By the inverse Fourier transform relation, the above relation becomes

$$E_{u'}(n) = \frac{4\overline{u'^2}}{\bar{u}} \int_0^\infty f(x)\cos\left(\frac{2\pi n x}{\bar{u}}\right)dx \tag{2.11}$$

Taking the limit as $n \to 0$, one obtains the means for determining the two turbulence scales. First,

$$\lim_{n \to 0}\left(\frac{\bar{u}E_{u'}(n)}{4\overline{u'^2}}\right) = \int_0^\infty f(x)dx = \Lambda_u \tag{2.12}$$

Second, the microscale is defined by

$$\lambda_u^2 = -\frac{2}{\left(\frac{\partial^2 f}{\partial x^2}\right)_{x=0}} \tag{2.13}$$

To obtain the second partial of f, one differentiates Equation 2.10 twice, and substituting the result into (2.13) yields

$$\lambda_u = \left(\frac{2\pi^2}{\bar{u}^2\,\overline{u'^2}}\int_0^\infty n^2 E_u(n)dn\right)^{-\frac{1}{2}} \tag{2.14}$$

The integrals in Equations 2 12 and 2.14 can be approximated for experimental purposes by summations over a finite frequency domain. The value of $E_{u'}(n)$ is derived from Equation 2.5 by substituting

$$n = \frac{1}{N_{tot}\Delta t} \tag{2.15}$$

where N_{tot} is the total sample size and Δt is the sample time interval.

2.2.2 Decay and Excitation

Turbulence is a dissipative phenomena, and the intensity will decay as viscous forces eventually convert the microscopic momentum fluctuations into molecular kinetic energy, raising the temperature of the fluid. This decay process is indicated by an increase in the microscale length, as the small parcels combine to form larger homogeneous parcels. The integral scale is also expected to grow, as small eddies combine to form larger eddies. The increasing integral scale and microscale should be accompanied by decreasing turbulence intensity.

Turbulent kinetic energy is dissipated most effectively by high frequency velocity fluctuations. The microscale responds strongly to high frequencies in the spectral distribution, as seen by the n^2 in the integrand of equation 2.14; its behavior is there-

fore directly related to the energy dissipation rate. Cebeci and Smith give the following equation for isotropic turbulent energy dissipation (Cebeci and Smith, 1974):

$$\dot{e}_u = \frac{d\overline{u'^2}}{dt} = -10\nu\frac{\overline{u'^2}}{\lambda^2} \tag{2.16}$$

The $\overline{u'^2}$ can be measured directly, and λ is derived from the Fast Fourier Transform (FFT) processing of the velocity fluctuations. Thus if the turbulence is freely decaying along a streamline, one would expect to find increasing microscale and decreasing $\overline{u'^2}$, resulting in a decreasing dissipation rate. On the other hand, if the microscale and $\overline{u'^2}$ are constant, the energy dissipation rate is constant, which would require constant turbulent energy input. This input is the sum of several terms representing production, diffusion, pressure work, and convection. Detailed treatment of these terms appears in Chapter 5 of Cebeci and Smith (Cebeci and Smith, 1974).

The decay process for turbulence intensity has been evaluated for free stream turbulence generated by a grid device. Galassi reported the dissipation model offered by Blair (Blair et al., 1983a) for a grid of cylinders of diameter b:

$$Tu = 0.78\left(\frac{l}{b}\right)^{-5/7}$$

Turbulence intensity decay in a turbine cascade passage has not been correlated. Three major factors are present that will influence the turbulence parameters: acceleration, turning, and shearing due to passage vorticity. It was expected that passage vorticity would increase the turbulence intensity as the flow approaches the passage exit.

2.3 Hot Wire Anemometry

It is generally accepted that the best low-cost tool for measuring rapidly fluctuating air velocity is the hot wire anemometer. The next step in accuracy is the laser velocimeter (or Laser Doppler Anemometer, LDA); an order of magnitude increase in cost and difficulty . Single component turbulence intensity (Tu_x) in a turbine cascade has been measured with a commercial *LDA* system (Priddy and Bayley, 1988).

Hot wires have limitations, since they possess a reactance, and because they must be inserted into the flow and therefore disturb it. Tungsten has a resistivity that is a strong function of temperature, and it is strong, so that microscopically thin wire, of low thermal inertia, can withstand the pressure forces due to the flow.

The controlling technique for the hot wire in this study was the constant temperature method: the wire is part of a Wheatstone bridge, and a current flows through it so as to raise the wire temperature to approximately 250 C. This temperature rise increases the resistance of the wire to a corresponding preset value. As the flow cools the

wire, the electrical resistance is reduced. The bridge voltage changes accordingly, and the controlling circuit applies more current to drive the temperature, and hence the resistance, of the wire back to its preset value. If the wire is small, it has low thermal inertia, and responds more closely to variations in the flow speed. The reactance of the current supply wires and the controller circuit can be compensated for, so that, up to a certain rolloff frequency, the bridge voltage is fairly closely following the speed variations. Figure 2.2 illustrates the main components of this system. Detailed treatment of hot wire anemometry can be found in Bradshaw (1971) and Hinze (1959).

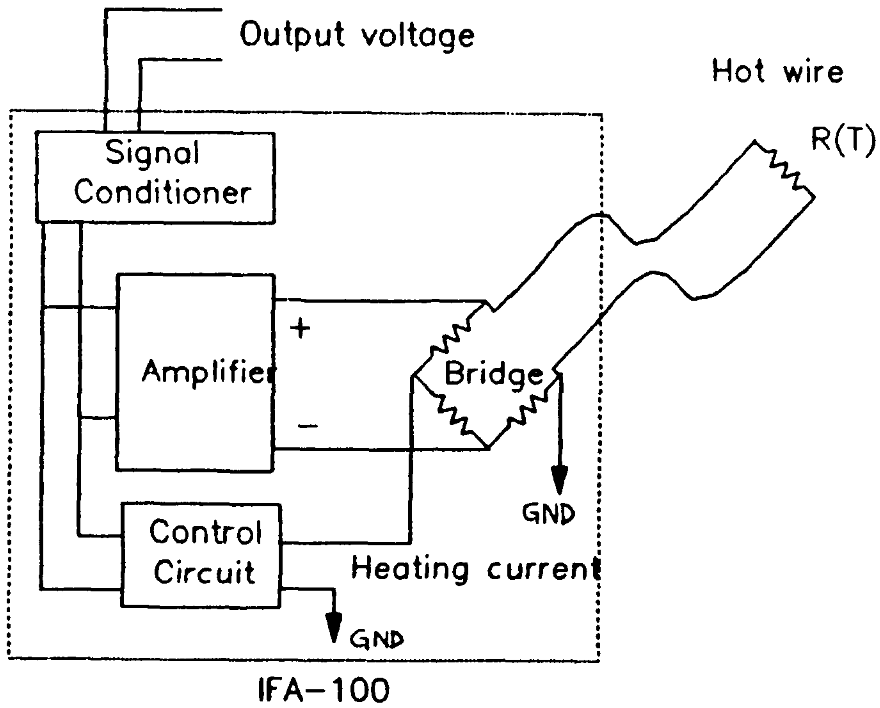


Figure 2.2 Hot Wire Schematic

Flow across each hot wire was modeled as uniform and normal to the wire; the voltage measured represents the effective speed, when the flow is actually a distribution of velocities along the wire, from a variety of directions. Conversion of voltages to effective speed is accomplished via calibration coefficients.

III. Apparatus

3.1 *Linear Turbine Cascade Tunnel*

This investigation was performed in the linear turbine cascade wind tunnel owned by the AFIT Aeronautics and Astronautics Department. Engineering drawings used for the construction of the tunnel exist at both AFIT/ENY and the Air Force Academy. The tunnel is a draw-down design powered by a centrifugal fan that turns at constant speed (3500 rpm). The wind tunnel flow speed was controlled manually, by adjusting variable angle inlet vanes at the fan inlet. The fan is a Buffalo Forge Model BL-365, and is powered by a 1.49 kW 240 volt electric motor.

The test section was designed for high-work turbine blade testing, and is equipped with four identical blades of aspect ratio one. Both span and true chord were 114.3 mm (4.50 in.). Four adjustable sideboards govern the flow entering and exiting the cascade. These were set to give a total turning angle of 108 degrees, and to give uniform entrance and exit velocity profiles. The inlet sideboards were set at 44.75 degrees from the test section X axis, which is normal to the blade row, to match earlier studies on the same blade profile (Moore et al., 1984; Langston et al., 1977; Galassi, 1989). Figure 3.1 is a plan view of the test section. The blades were produced from manually digitized data (Appendix A), derived from drawings by Moore. The Y axis is parallel to the blade row, and the plane Z = 0 is defined by the test section floor.

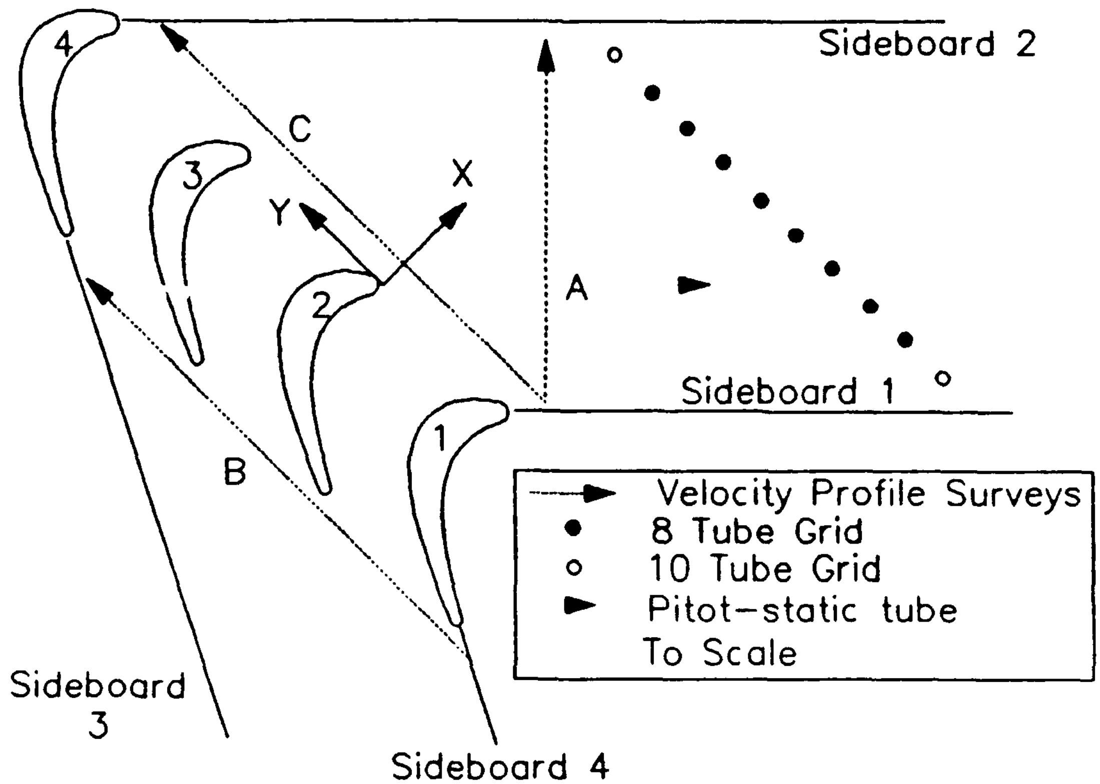


Figure 3.1 Test Section Planview

The test section ceiling was modified specifically for this study to allow the insertion of a pitot tube and/or a hot wire probe through the plexiglas top into any area of the cascade passage surrounding the two inner blades. A large plexiglas disc (Disc 2) was inserted into a circular cutout in the test section ceiling, and was free to rotate above the blades. An off-center circular cutout in Disc 2 held a smaller plexiglas disc (Disc 1). Both discs were fitted with handles for manual rotation, and Disc 1 was drilled to recieve a pitot tube mount and a hot wire probe mount. A two-arm index device was

constructed to track the position and orientation of the hot-wire probe mount as it was moved through the passage (see Figure 4.1 for details). The upper surfaces of the blades and sideboards were covered with felt to reduce leaks and to prevent scratching of the undersurfaces of the two rotating disks.

All four blades were bolted to a phenolic panel that inserted upwards into the aluminum alloy floor of the test section. Tubing and wires leading to the instrumented blade were routed upwards through this panel, and did not intrude into the cascade passages.

3.2 Jet Grid Device

A jet grid device was used to vary the freestream turbulence. Eight tubes were inserted vertically into the test section upstream of the blade row and parallel to the Y axis. Velocity profile problems led to the addition of two outer tubes (Figure 3.1). Each tube was blocked internally at the lower end, and supplied with pressurized air on the upper end through air-tool style quick-disconnect fittings. Holes were drilled completely through the tubes at eight locations 12.7 mm (0.5 in.) apart, starting 6.3 mm from the lower end of the tube (Z = 6.3 mm). The orifice diameter was identical for all the holes on all the tubes, at 1.17 mm (.046 in.). This diameter was selected to give a total orifice area per tube larger than the tube inner cross section area, which caused the flow to choke prior to reaching any orifices.

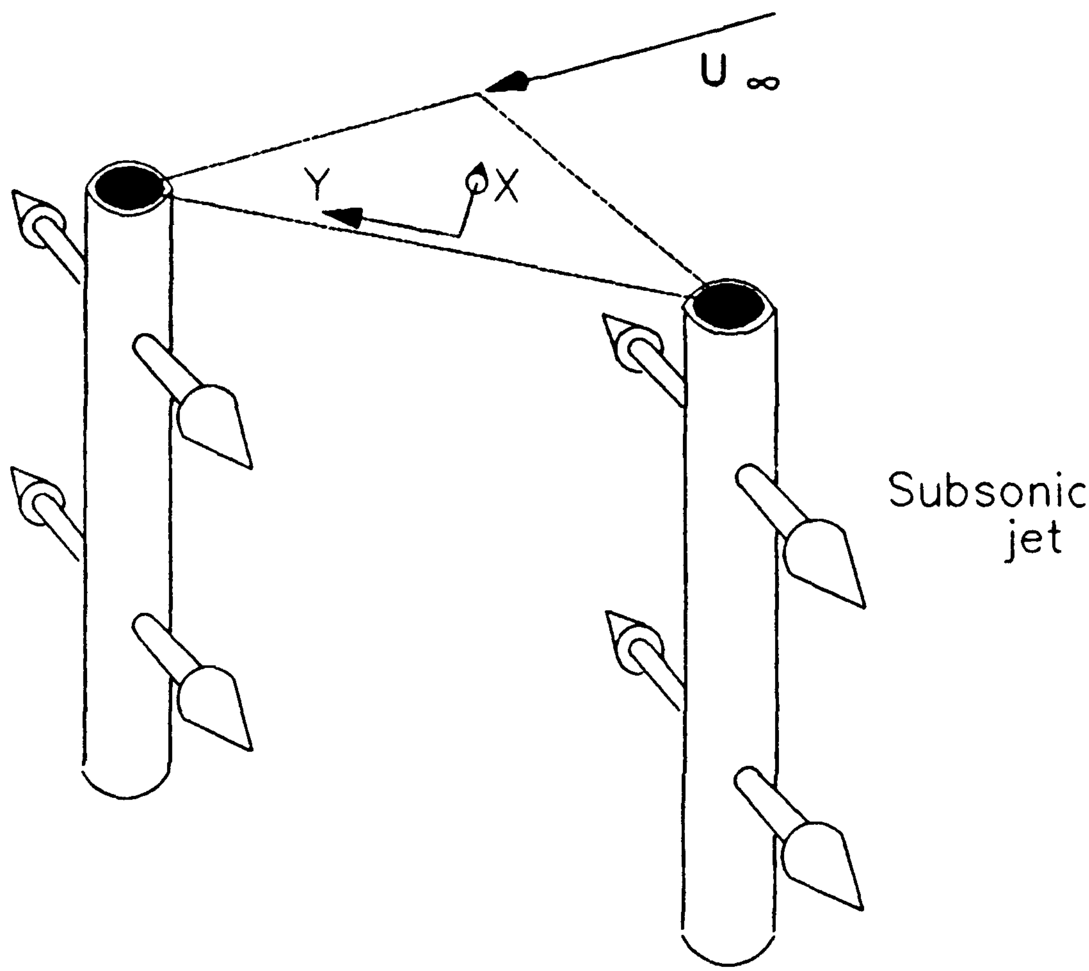


Figure 3.2 Jet Grid Orientation in the Primary Flow

The orifices provided a grid of high speed (but subsonic) jets to impinge on the primary inlet flow (Figure 3.2). Studies by Galassi indicated that the orientation of the jets should be normal to the freestream velocity, to study the effect of turbulence scale length while holding turbulence intensity relatively constant (Galassi, 1989).

During this study, the location of the grid device, the orientation of the jets, and the size of the tube orifices, were fixed. Table 3.1 gives the specifications of the jet grid.

Table 3.1 Jet Grid Specifications

Tube spacing, center to center	25.40 mm
Tube outer diameter (*b*)	6.35 mm
Tube inner diameter	4.60 mm
Injection orifices/tube	16
Orifice diameter	1.17 mm
Orifice orientation	Cross-flow
Grid Location (*l*/*b*)	25.7

The cylindrical plenum supplying air to the grid tubes was fitted with an Endevco pressure transducer and an iron-constantan thermocouple, mounted in the middle of the plenum. Air entered the plenum simultaneously from both ends of the cylinder: one port to the shop air dryer/filter assembly, and one port to an auxiliary compressor. A pressure regulator provided manual control of the plenum pressure, which ranged from zero to 60 psi.

3.3 *Data Acquisition System*

Electronic data acquisition was accomplished with a Hewlett-Packard 3852A equipped with a digital voltmeter, high-speed voltmeter, 3 FET modules and a Relay Actuator module. This system was controlled by a Zenith 386/387 PC via a GPIB interface. Controlling software was written using Microsoft QuickBASIC, and is listed in the appendix.

For turbulence measurement, the FET module attached to the hot-wire probe controller became a dedicated high-speed module: it was connected directly to the high-speed voltmeter with an internal ribbon cable. This cable was disconnected during the probe calibration process.

3.4 Instrumented Blade

Blade #2 (Figure 3.1) was equipped with 23 surface pressure taps, and 28 thermocouples for heat transfer measurement. A thin (.002 in. nominal) stainless steel foil was mounted around the blade contour, starting from near the trailing edge, proceeding forward around the nose and back to near the trailing edge (Figure 3.3). This foil was powered by a DC current of approximately 15 amps, provided by a 100 amp DC power supply. A digital voltmeter and an analog ammeter were used to measure the electrical power input.

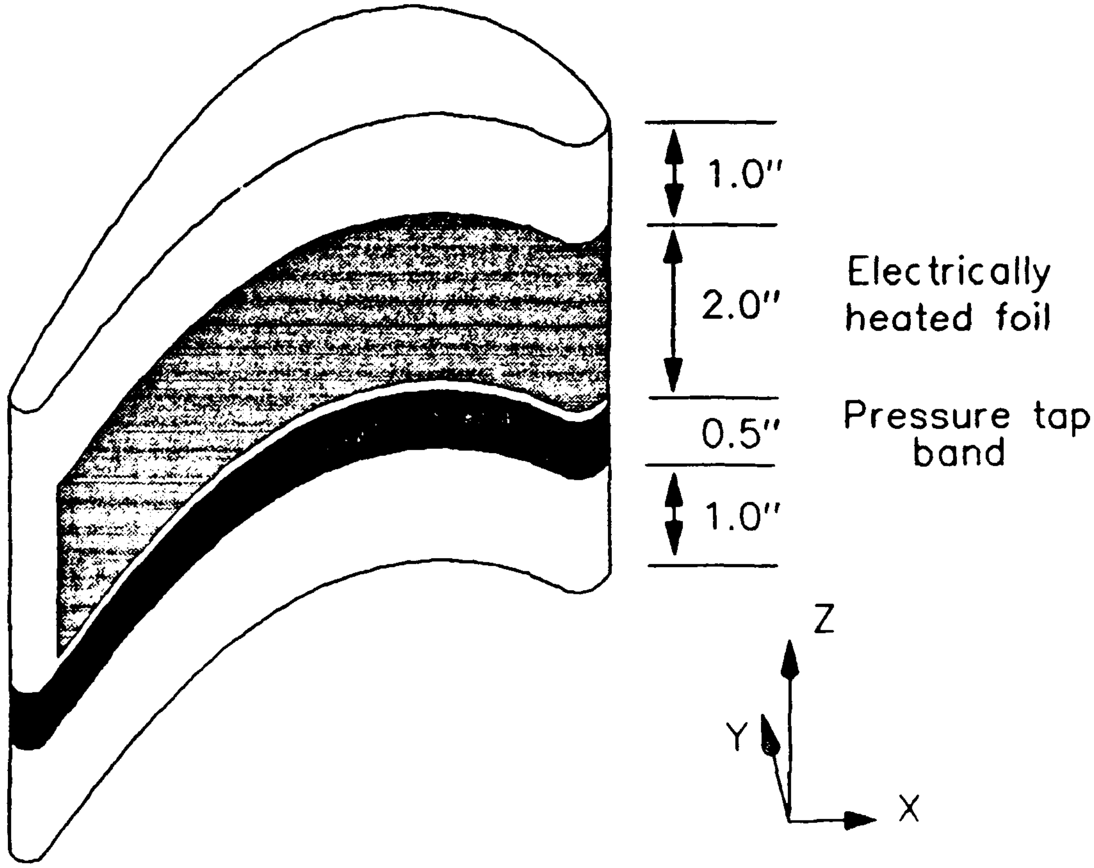


Figure 3.3 Blade 2 Instrumented Surface Regions

The thermocouples were mounted along the centerline of the foil ($Z/c = 0.56$). Surface pressure taps were mounted in staggered groups of three in the band indicated in Figure 3.3. Table 3.2 lists the location of the static pressure taps; surface thermocouple locations are identical to the static pressure tap locations with the exception of number 10, which had to be moved toward the leading edge to keep it under the foil. Details on blade profile and construction are found in Appendix A.

Table 3.2 Static Pressure Tap Locations

Tap No.	x/c	s/c	Blade Region
1	0.01739	0.00000	Suction Surface
2	0.06522	0.08772	Pressure Surface
3	0.1244	0.1991	Pressure Surface
4	0.1913	0.3246	Pressure Surface
5	0.3156	0.4474	Pressure Surface
6	0.4365	0.6184	Pressure Surface
7	0.6000	0.8026	Pressure Surface
8	0.7687	0.8974	Pressure Surface
9	0.8522	0.9763	Pressure Surface
10	0.93235	1.0290	Pressure Surface
11	1.0000	1.1815	Trailing Edge
12	0.9026	1.1167	Suction Surface
13	0.7643	1.0088	Suction Surface
14	0.6670	0.9035	Suction Surface
15	0.5817	0.8026	Suction Surface
16	0.4870	0.6974	Suction Surface
17	0.3852	0.6404	Suction Surface
18	0.3322	0.5252	Suction Surface
19	0.2191	0.3991	Suction Surface
20	0.1078	0.2737	Suction Surface
21	0.03565	0.1298	Suction Surface
22	0.00000	0.07460	Suction Surface
23	0.008696	0.0395	Suction Surface

3.5 Pressure Measurement

Electronic measurement of pressure was performed with a Scanivalve (2 psi module) selector. The 48 port selector stepper motor was driven by a Scanivalve controller and checked with a channel

indicator. The transducer selectively sampled 28 taps (23 blade pressures, 2 pitot-static pressures and 3 atmospheric). The transducer required 10.0 volts supply power (provided by a 2 amp power supply), and the signal was amplified with a Neff DC amplifier prior to input into the HP3852A FET module. The stepper motor controller was driven by the Relay Actuator module of the HP3852A.

Two distilled water manometers provided direct pressure measurement. One provided two and a half digit accuracy in inches of water, and was used for velocity surveys and to cross check the Scanivalve. The second was a micromanometer, providing four and a half digit accuracy in inches of water, and was employed during the probe calibration process.

3.6 Temperature Measurement

Blade surface temperature was measured by 23 iron-constantan (Type J) thermocouples. Twenty two of these were attached to the undersurface of the electrically heated foil; one was mounted on the trailing edge, beyond the edge of the foil. Five internal thermocouples measured the blade core temperature. Room temperature and tunnel temperature upstream of the cascade were also measured by thermocouple. During probe calibration, a thermocouple was used to record room and calibration tank temperature. All these were Type J.

The thermocouples were read with an Omega Digicator during checkout, and then attached to the HP3852A Data Acquisition Unit for

sampling during experiments. The HP device reads the thermocouples through 2 FET modules, and uses an electronic reference temperature to convert the voltage to celsius temperature.

3.7 *Velocity Measurement*

The free stream inlet velocity profile was determined using a pitot-static tube inserted through Disk 1 in the test section top. During initial tests, the hot wire probe was mounted in Disk 1, and moved to location C at the center passage entrance (see Figure 5.6a), and the pitot-static tube was mounted between the cascade inlet plane and the jet grid (Figure 3.1). During the passage turbulence investigation, the hot wire probe was moved to 15 locations within the center passage, and the pitot-static tube remained fixed in the location depicted in Figure 3.1.

The turbulence frequency measurement goal dictated the use of tungsten wire probes, which have better frequency response than film probes. The test section geometry lends itself to use of the cross-flow type of probe, although end-flow probes can be used with an elbow fitting. The two-channel X-wire probe was selected to provide angle information as well as speed. The TSI model 1240-T1.5 (wire diameter 0.00015 in., or 3.8 micron) was used exclusively for this study. The T1.5 sensor has a cutoff frequency above 400 kHz.

The calibration of the TSI probes was accomplished with a TSI calibration tank supplied by shop air at low pressure. A TSI Intelligent Flow Analyzer (IFA-100) controlled the probe heating current

(Figure 2.1) and provided conditioned voltages to the HP 3852A for measurement, both during calibration and cascade flow measurement. An oscilloscope provided qualitative information on the probe performance during calibration and flow measurement.

IV. Procedures

4.1 Calibration

4.1.1 Pressure Transducer

The Scanivalve pressure transducer was calibrated by manually applying a fixed pressure to both the water manometer and the Scanivalve. Both devices referenced the pressure to atmospheric. The HP3852A voltmeter measured the amplified voltage 50 times, averaged the values, and sent the data to the PC for storage and curve fitting. This process was repeated for both positive and negative gauge pressures. The SCANCAL QuickBASIC program (Appendix C) drove the data acquisition system for this calibration.

The data fit a straight line until near the end of the transducer range. This allowed use of the HP3852A internal data conversion subroutine for pressure data, which employs the endpoints of the line fit to compute the pressure. The subroutine PRUN in MAINDRV3 contains the necessary commands to use the HP subroutine.

4.1.2 Heat Transfer

The surface heat transfer was driven by electrical resistance heating of the foil. Accurate computation of the heat generation term in the energy balance equation required accurate knowledge of the electrical resistivity (ρ) of the foil material. A separate experiment was performed to derive this material property at vari-

ous temperatures. Details are found in Appendix B.

4.1.3 Hot Wire Anemometer

The calibration of the probes required knowledge of the orientation of the tungsten wires, which are invisible to the unaided eye. A microscope was adapted for this purpose by fitting a human hair reticle and a protractor onto the eyepiece. Details on this arrangement appear in the Appendix C.

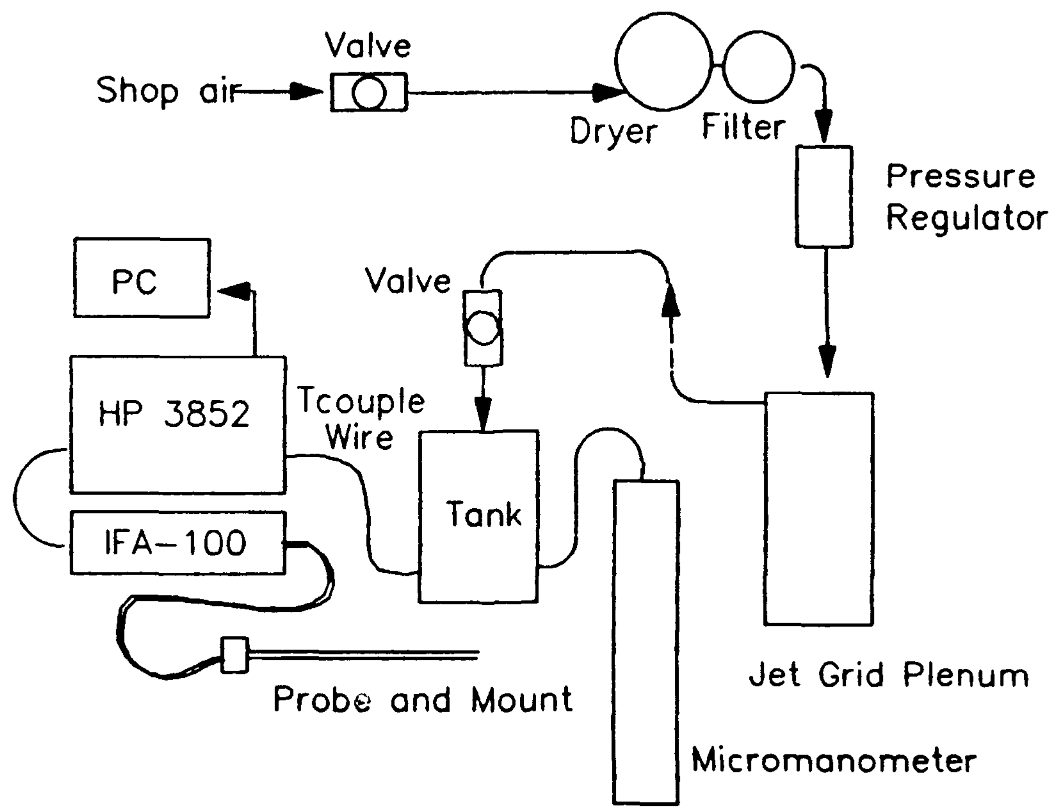


Figure 4.1 Hot Wire Calibration Block Diagram

The calibration method involved rigging a calibration tank with a rotating probe mount. The TSi model 1125 tank provided the

necessary velocity range. Figure 4.1 is a block diagram illustrating the components used for this method. The shop air was routed through the jet grid plenum solely for plumbing convenience. Duct tape held the tank to a plywood platform fitted with set screws, which provided for small adjustments in the orifice height. C-clamps held the platform to the metal platform underneath, to which was attached the probe mount arm. A protractor was fixed to the outer post, as seen in Figure 4.2. The pointer is clamped to the probe mount holder, and provides the necessary angle measurements for the calibration procedure described in the appendix.

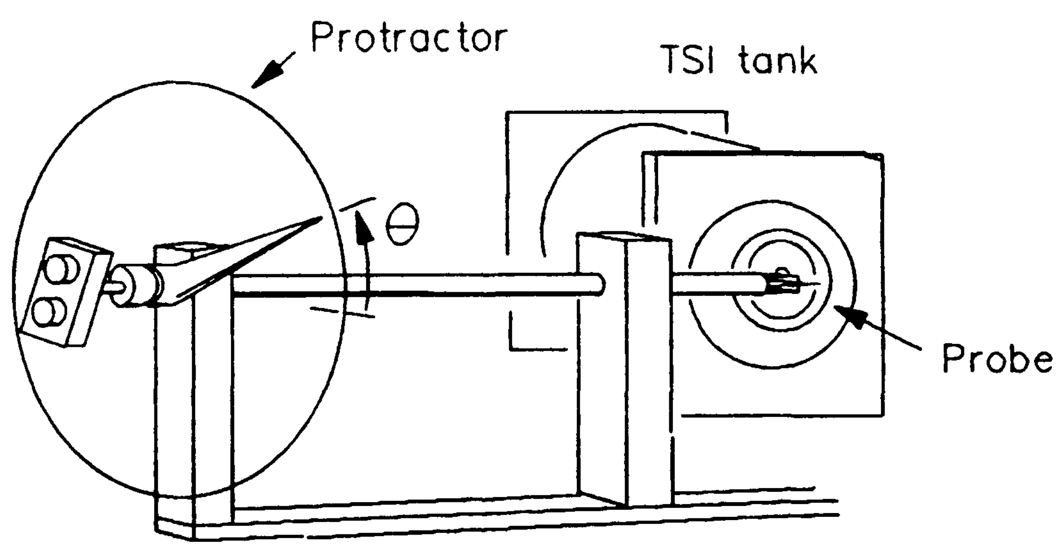


Figure 4.2 Calibration Rig Detail

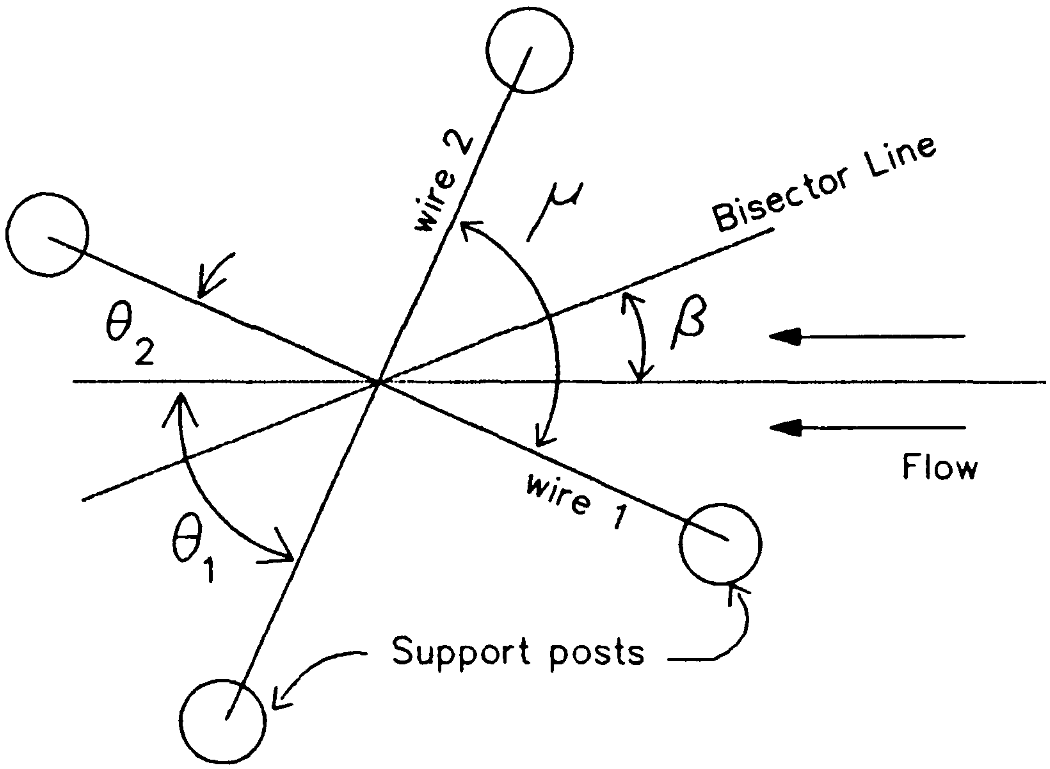


Figure 4.3 Hot Wire Flow Geometry

The model for the calibration is identical to that used by Galassi (Galassi, 1989). The geometry of the flow is shown in Figure 4.3. The *MathCAD* worksheet PROBECAL.MCD (Appendix C) fits the voltage/velocity data to the curves

$$E1 = b_0 + b_1 \cdot (U_{1eff})^{1/2} + b_2 \cdot U_{1eff} \tag{4.1}$$

$$E2 = b1_0 + b1_1 \cdot (U_{2eff})^{1/2} + b1_2 \cdot U_{2eff} \tag{4.2}$$

For the flow orientation depicted in Figure 4.3, the N measured freestream velocity values are converted to N effective velocity pairs U_{1eff}, U_{2eff} defined as

$$U_{1eff}^2 = U_{\infty}^2(\cos^2\theta_1 + k_1\sin^2\theta_1) \tag{4.3}$$

$$U_{2eff}^2 = U_{\infty}^2(\cos^2\theta_2 + k_2\sin^2\theta_2) \tag{4.4}$$

For the first iteration, the angle calibration coefficients k_1 and k_2 are assigned values between zero and one. The calibration coefficients are converted to vectors:

$$\vec{b} = \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} \qquad \overrightarrow{b1} = \begin{bmatrix} b1_0 \\ b1_1 \\ b1_2 \end{bmatrix}$$

Two matrices (*N* by 3) are constructed from Equations 4.1 and 4.2 using the *2N* values of effective velocity:

$$W1 = \begin{bmatrix} 1 & U_{1eff1}^{1/2} & U_{1eff1} \\ 1 & U_{1eff2}^{1/2} & U_{1eff2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ 1 & U_{1effN}^{1/2} & U_{1effN} \end{bmatrix}$$

and similarly for W2 in powers of U_{2eff}. The corresponding *N* voltage pairs (E1, E2) are converted to two vectors:

$$\overrightarrow{E1^2} = \begin{bmatrix} E1_1^2 \\ E1_2^2 \\ \cdot \\ \cdot \\ E1_N^2 \end{bmatrix} \qquad \overrightarrow{E2^2} = \begin{bmatrix} E2_1^2 \\ E2_2^2 \\ \cdot \\ \cdot \\ E2_N^2 \end{bmatrix}$$

One can now solve for the velocity coefficient vectors via the matrix algebra equations

$$\vec{b} = (W1^T \cdot W1)^{-1} \cdot (W1^T \cdot \overrightarrow{E1^2}) \tag{4.5}$$

$$\overrightarrow{b1} = (W2^T \cdot W2)^{-1} \cdot (W2^T \cdot \overrightarrow{E2^2}) \tag{4.6}$$

The first iteration is now evaluated by summing the squares of the error (SSE) for the N pairs of measured and predicted voltage for Channel 1. This computation is repeated for Channel 2. The values of k1 and k2 are adjusted (manually in the last page of the worksheet) and the second iteration begins. This process is repeated until the two SSE values are minimized. The eight calibration values are now ready to be stored in a file under the probe serial number and room temperature, where they can be recalled by the QuickBASIC program TUBAT3 for data reduction.

As one of the goals was to move the probe throughout the passage between the blades, where the average streamline orientation was not known, it was considered important that the calibration model be robust with respect to the angle β. This is the angle between the streamline and the probe bisector (also called θ during calibration). Accordingly, the angle θ was varied from -20 to +20 degrees during the calibration (Figure 4.2).

Results from the first calibrations showed that, while the outer wire (Channel 1) showed an excellent curve fit, the inner (Channel 2) wire curve fit was adequate only within 10 degrees, and fell off most rapidly for negative values of θ. Outside of 10 degrees of offset, the measured voltages were much lower than predicted by the model of Equations 4.1 and 4.2, which appeared to work well for the outer wire over larger values of θ.

Reasons for this effect are found in the flow geometry that the inner wire experiences on cross-flow probes. Figure 4.4 illustrates the flow anticipated in the plane of the inner wire, which is normal to the four support posts, for negative values of θ. A wake from one of the two outer wire support posts will impinge on the inner wire, and in this region of the inner wire, flow will be turbulent, improving heat transfer and causing the wire temperature (and hence resistance) to decrease in this region. This effect is dominated, however, by the greatly reduced flow speed in the wake, so that the net effect is a lower flow speed when averaged across the length of the inner wire. The IFA-100 operates so as to maintain the wire resistance nearly constant, so that as the wire resistance rises due to a drop in the average flow speed, the heating current is reduced and therefore the measured voltage is also reduced.

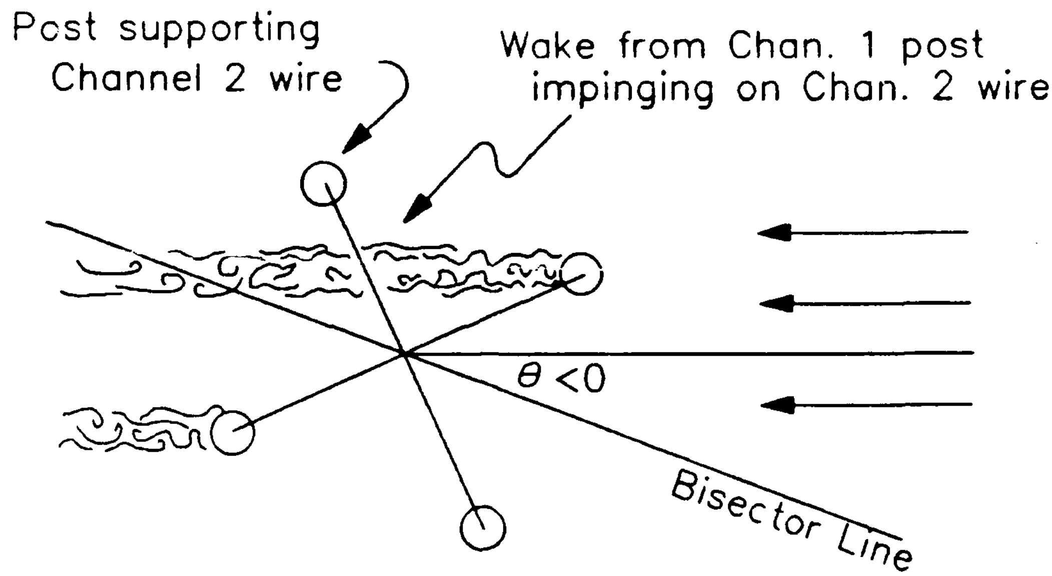


Figure 4.4 Probe End View: theta < 0

For positive θ, the cause of the excursion from predicted voltage values is less clear. Figure 4.5 shows that no wakes affect the wire for this orientation. Since the measured voltages are still less than predicted by the model, one might deduce that the flow speed is reduced, but the cause is not obvious.

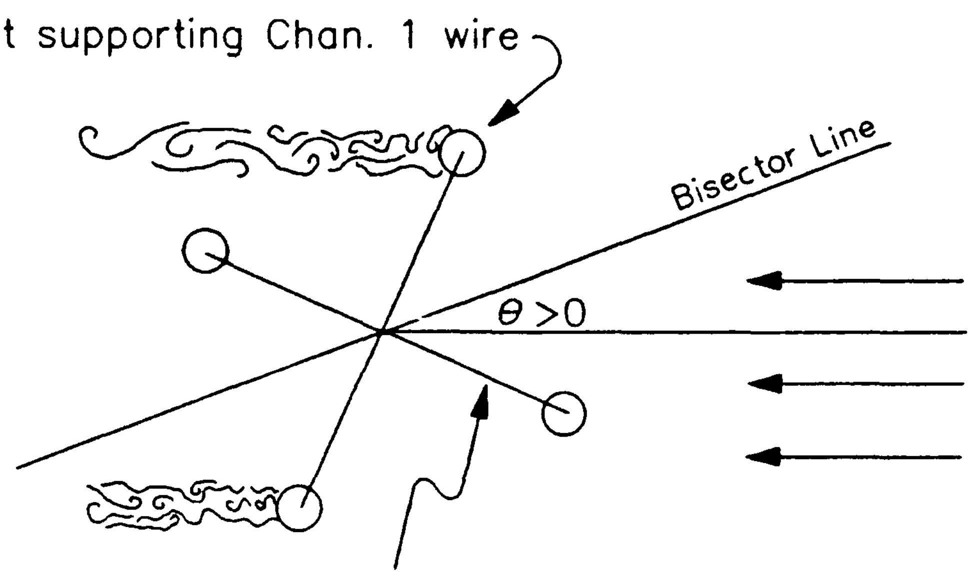


Figure 4.5 Probe End View: theta > 0

At this point, adjustment to the calibration model was discussed. A model allowing better curve fit on the inner wire, using more terms of a Taylor series expansion, was considered. The nature of the wake, however, was the deciding factor. While the positive θ orientation problem could have been improved, the negative θ problem could not. The positive θ flow, while no longer uniform, is still laminar. In contrast, the wake region of the negative θ flow is turbulent, and dependent on Reynolds number effects. The calibration tank jet is a low-turbulence flow, so that during calibration the wake turbulence is relatively free of free-stream turbulence effects. But since the cascade tunnel flow would possess a high level of free-stream turbulence, induced by the jet grid, the effect of this turbulence on the wake impinging

on the inner wire would not be known, and could not be duplicated during calibration without great difficulty. The flow model of Equations 4.1 and 4.2 was considered adequate for this initial study.

4.2 Data Acquisition

4.2.1 General

A one-hour warm up period was allowed for the HP3852A prior to any measurements. During this time, the tunnel fan was turned on and a nominal 15 amp current applied to the #2 blade foil to bring the interior of the blade to steady state. This required about 30 minutes, and it also brought the room temperature up 2 to 3 degrees, where it stabilized.

The MAINDRV3 program (Appendix D) was used to drive the HP3852A in measuring and recording data on 1.2 MB floppy disks. Five complete scans fit on one floppy in this manner, with enough room left for the velocity files generated by the TUBAT3 program during the reduction process. A complete scan included first a pressure survey, followed by a temperature/heat transfer survey and a hot-wire probe survey. The pressure survey had to precede the temperature survey because local pressure coefficient was used to generate local Reynold's number for computation of local Stanton number.

The pressure survey required two minutes, because the Scanivalve employs a time delay for each channel to allow the trans-

ducer diaphragm to come to equilibrium before the voltage is read. The MAINDRV software then directed the HP3852 voltmeter to take 50 voltage readings and average them. This averaged value was then converted to kPa using the HP3852 conversion subroutine, and the pressure was recorded. The 28 pressures (23 surface taps + 2 pitot-static ports + 3 atmospheric) thus sampled were therefore not instantaneous. The surface taps were sampled first, in numerical order, punctuated by three atmospheric taps to reveal channel skipping by the Scanivalve controller. The pitot-static tube was sampled last. All pressures were gauge, referenced to atmospheric.

After completion of the pressure survey, the blade and tunnel temperature survey was initiated, and was normally completed within a minute of the termination of the pressure survey. 28 blade thermocouples, plus one ambient and one tunnel temperature were recorded.

The recording of hot-wire voltages produced by the IFA-100 took place less than a minute after the thermal survey. A special subroutine (FRUN) written by Galassi (Galassi, 1989) configured the HP3852 high speed voltmeter to measure two hot wire voltages every 0.00002 second, producing 2048 voltage pairs (termed a "scan"). During the heat transfer investigation, these readings were taken at location C, at the inlet to the passage between #2 and #3 blades. During the passage turbulence investigation, three

scans were taken less than a minute apart at each location. Three scans per location provided a measure of repeatability, and helped overcome the inability of the voltage reduction algorithm to reduce certain flow geometries (see Section 4.3). When the probe had been moved to a new location, the location coordinates and bisector angle (ψ_L) in the test section reference frame were updated first, so as to be available for permanent storage with the hot-wire voltages.

4.2.2 Probe Location and Orientation

The hot-wire probe was inserted into the mount with the entire index-arm/Disc 1 removed from the test section. This enabled the angle between the bisector and index arm 2 (α) to be inspected with a magnifying glass, and the protractor for α to be adjusted to fix the bisector at the 0/360 degree marking on the protractor. The depth of the hot wires from the test section ceiling was also easily measured at this time. The depth setting remained constant throughout this study at 47% blade span, placing the probe wires at Z/c = 0.53. Then the entire apparatus was lowered into position so that index arm 1 fit over its mounting post on the test section, and Disc 1 fit into the eccentric cutout on Disc 2. The location of the probe mount was then adjusted by turning the discs, either to reproduce a location (recorded manually as a vector of three angles: $\langle\gamma, \beta, \alpha\rangle$), or to investigate a new location. A subroutine (LOCN) in MAINDRV3 converted the index

arm angles to test section coordinates (X, Y) and bisector angle (ψ_L) in the test section reference frame (Figure 4.6). The heat transfer study used location C as the standard probe location (see Figure 5.6a).

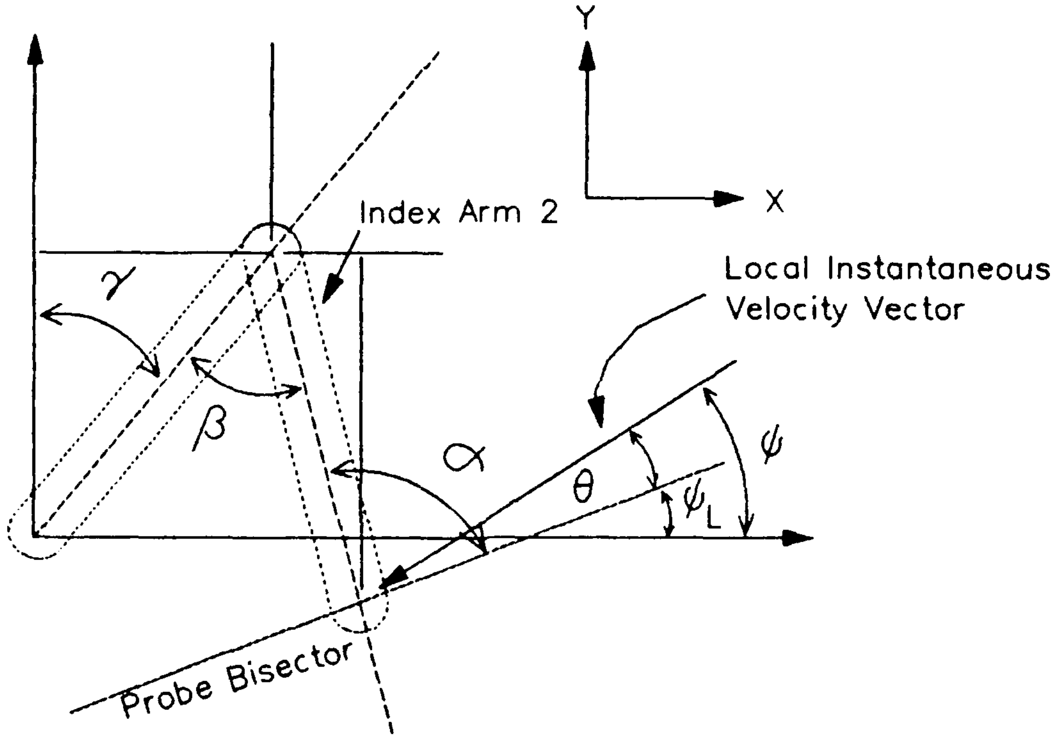


Figure 4.6 Probe Location Angles

A weakness due to flow geometry exists in the data reduction algorithm (see Section 4.3); this made the orientation of the probe a critical matter, and a qualitative look at the turbulence was necessary, before taking a scan of voltages, to ensure the angle β_L between the bisector and the instantaneous flow vector did not exceed the acceptable range.

In the cascade passage, this step was initially a guess, and the oscilloscope was used to refine the guess. By alternating the display between Channel 1 and 2, and adjusting α (Figure 4.6) so that the band containing the fluctuating voltages was "matched" in amplitude to the other channel, and the fluctuating signal was relatively free of intermittent wild swings, the chance of laying the bisector on the average flow vector was (theoretically) maximized. This technique worked most of the time: $\bar{\beta}$ (Figure 4.3) during the passage turbulence investigation ranged from half a degree to over sixteen degrees. However, wild voltage swings (e.g., a sudden drop of about two volts on Channel 2) still caused two out of three scans to fail when $\bar{\beta}$ was small (only -7.6 degrees at location F, Figure 5.6a, and only 2 degrees near the pressure side), while all three scans succeeded at location H, which had $\bar{\beta}$ of -12.4 degrees. This phenomenon will be discussed further in the next section.

4.3 *Data Reduction*

Pressure and thermal data were reduced immediately on recording the pressures and temperatures by the MAINDRV program; pressure coefficient and temperature plots were displayed for qualitative analysis immediately after measurements. The hot-wire voltage data had to be converted to velocity and velocity fluctuations using the calibration coefficients appropriate for the ambient temperature at which the data was taken. This conversion process was a simultaneous solution of two equations to obtain effective velocity across

each wire. These effective velocity pairs were then reduced to pairs of flow angle and flow speed (β_i, $U_{\infty i}$) and component velocities in the probe reference frame (u_i, v_i). The u component paralleled the bisector and the v component lay normal to the bisector but in the same horizontal plane.

Solving Equations 4.3 and 4.4 for U_∞^2 yields

$$U_\infty^2 = \frac{U_{1eff}^2}{\cos^2\theta_1 + k_1\sin^2\theta_1} = \frac{U_{2eff}^2}{\cos^2\theta_2 + k_2\sin^2\theta_2} \tag{4.7}$$

Since θ_1 and θ_2 were nearly complementary angles (within 1/2 degree), one can set $\cos^2\theta_2 = \sin^2\theta_1$ and $\sin^2\theta_2 = \cos^2\theta_1$, so that (4.7) can be manipulated to give

$$U_{1eff}^2(\cos^2\theta_2 + k_2\sin^2\theta_2) = U_{2eff}^2(\sin^2\theta_2 + k_1\cos^2\theta_2) \tag{4.8}$$

Dividing by $\cos^2\theta_2$ and solving for θ_2 :

$$U_{1eff}^2(1 + k_2\tan^2\theta_2) = U_{2eff}^2(\tan^2\theta_2 + k_1) \tag{4.9}$$

$$\tan^2\theta_2(U_{1eff}^2 k_2 - U_{2eff}^2) = U_{2eff}^2 k_1 - U_{1eff}^2 \tag{4.10}$$

$$\theta_2 = \tan^{-1}\left[\left(\frac{U_{2eff}^2 k_1 - U_{1eff}^2}{U_{1eff}^2 k_2 - U_{2eff}^2}\right)^{1/2}\right] \tag{4.11}$$

If $\alpha = \pi/2 - \mu/2$, then the angle of the flow from the bisector is

$$\beta = \alpha - \tan^{-1}\left[\left(\frac{U_{2eff}^2 k_1 - U_{1eff}^2}{U_{1eff}^2 k_2 - U_{2eff}^2}\right)^{1/2}\right] \tag{4.12}$$

At this point, both θ_1 and U_∞ can be determined from (4.7). In the program TUBAT3, β and U_∞ are averaged and stored for later use, then used for computation of the velocity components u and v in the probe bisector reference frame (u is parallel to the bisector, v is perpendicular). This entire computation is repeated for the 2048 pairs of voltages recorded by the FRUN subroutine of MAINDRV3.

It was at this step that the algorithm was discovered to be less than fully robust. In processing a file of 2048 voltage pairs (E1,E2), an occasional drop in magnitude of approximately two volts on either E1 or E2 caused the following value to become negative:

$$\sigma = \frac{k1 \cdot U2_{eff}^2 - U1_{eff}^2}{k2 \cdot U1_{eff}^2 - U2_{eff}^2} \tag{4.13}$$

where k1 and k2 are angle calibration constants.

In the simultaneous solution of the equations for β (Equation 4.12), this value is the argument of a square root:

$$\beta = \frac{\pi}{4} - \tan^{-1}(\sqrt{\sigma}) \tag{4.14}$$

For some scans, the fatal combination of voltages appeared early in the string; in others, nearly at the end. One might speculate that the instantaneous flow vector is swinging around suddenly to cause one of the wires to experience effective velocities that decrease to zero and then increase negatively, a condition to be expected when v becomes of the same order as u. An alternative theory is to fix the blame on the number 2 wire, as it momentarily recieves a larger than

normal dose of the wake from the number 1 wire support post. This turbulent but low speed wake may appear as nearly stagnated flow from a cooling perspective. Improvement to the algorithm was not pursued in this study.

V. Results

5.1 General Test Section Flow Data

5.1.1 Cascade Velocity Profiles

The cascade test section entrance region was traversed with a pitot-static tube, along a horizontal line perpendicular to the entrance sideboards, approximately 2 cm upstream of the leading edge of blade #1 (Survey A, Figure 3.1). Next, the cascade exit region was traversed along a horizontal line parallel to the test section Y axis, approximately 1 cm downstream of the blade trailing edges (Survey B). The entrance region was then traversed along a similar line held parallel to the test section Y axis, again approximately 2 cm upstream of the blade leading edges (Survey C). The pitot-static tube depth was set for mid-span for all surveys, and the orientation was held parallel to the appropriate sideboard.

The results (Figures 5.1, 5.2) show that the flow without the grid is uniform as it approaches the cascade, with some acceleration near sideboard 1 (Figure 3.1). This acceleration is attributed to the influence of the pressure gradient near the suction surface of blade 1. The flow decelerates anead of the blade leading edges, and continuity causes the flow to accelerate in the region ahead of the passages. Hot wire measurements in the passage entrance region indicated that the flow was already turned by as much as 15 degrees before it entered the passage mouth. The exit profile is more uniform than the entrance profile.

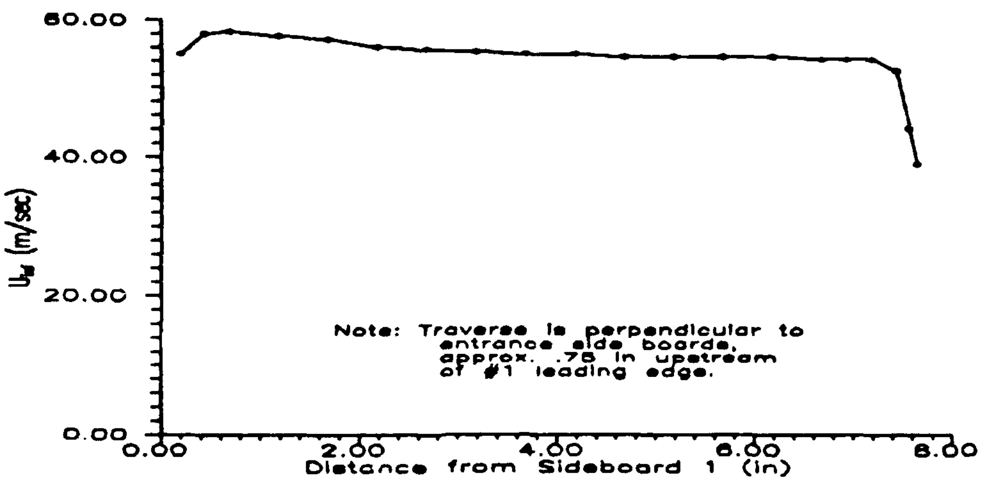


Figure 5.1 Survey A: Inlet Velocity Profile, No Grid

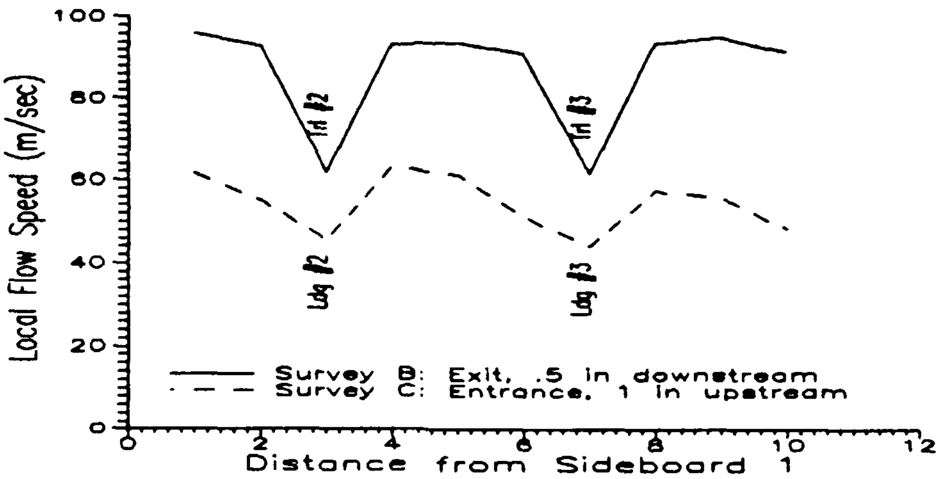


Figure 5.2 Cascade Entrance/Exit Velocity Profiles, No Grid (Surveys B and C)

Insertion of the grid caused significant changes in the pressure field of the inlet region. Initially, an eight tube grid was used, but this led to high speeds near the sideboards that changed the effective angle of incidence. This non-uniform velocity profile worsened with the addition of secondary flow. A ten-tube grid was installed to correct this leaking, and the sideboards were modified in an attempt to obtain uniform flow in the vicinity of

blade 2. Figure 5.3 depicts the results of these modifications; the sawtooth appearance of the profile near sideboard 2 is the wake effect of the jet grid tubes (see Figure 3.1, survey path A).

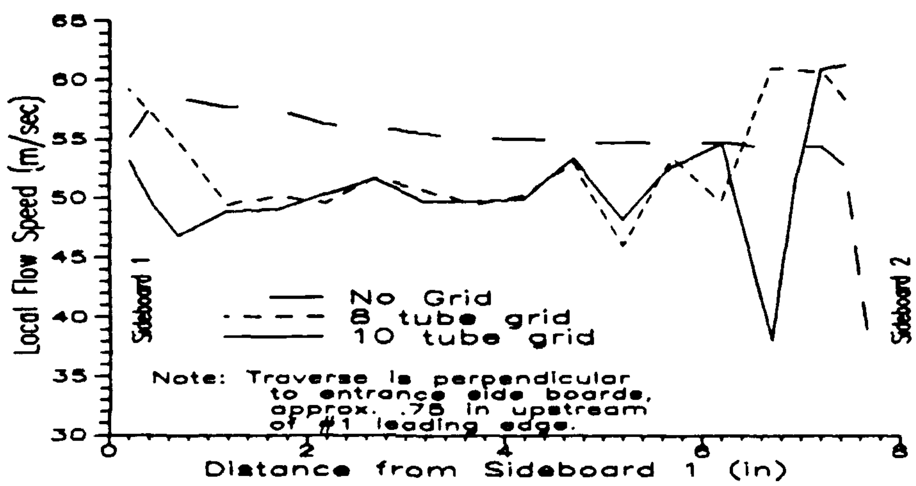


Figure 5.3 Inlet Velocity Profiles, Path A

The introduction of two outer jet grid tubes reduced but did not eliminate the peaks in the velocity profile near the sideboards. Figures 5.4 and 5.5 are velocity profiles on the survey path parallel to the Y axis (path C in Figure 3.1).

A small rounded ramp was added to Sideboard 2 to reduce the gap between it and the outer jet-grid tube (Survey F in Figure

5.4). Sideboard 1 was extended upstream to reduce the gap between it and the nearest jet-grid tube (Survey G in Figure 5.4). With no secondary flow, it appeared that the flow entering the cascade on both sides of blade 2 was symmetrical, and would not cause a change in the angle of incidence.

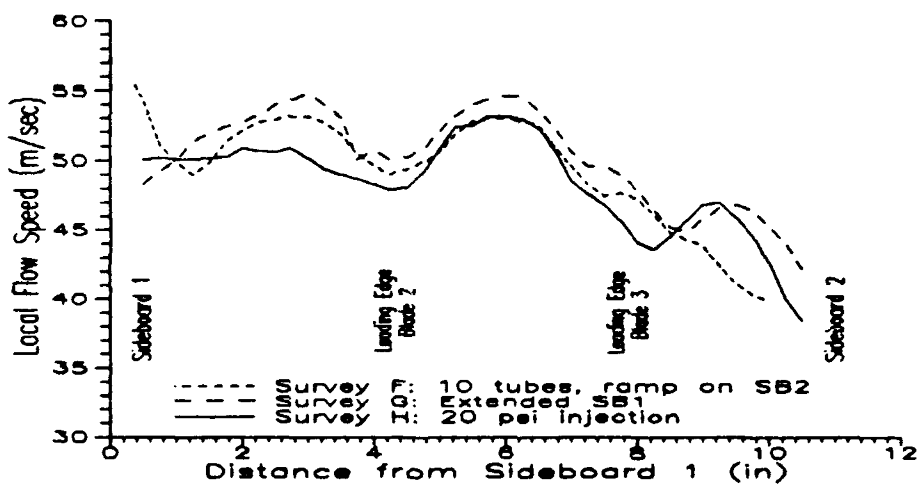


Figure 5.4 Cascade Entrance Velocity Profiles, Path C, 10 Tube Grid

Survey H in Figures 5.4 and 5.5 showed that these efforts were not successful. The inlet flow appeared fairly uniform on both sides of blade 2 without blowing, but secondary injection (20

psi) changed the profile again; the center passage inlet velocity was significantly higher than that for the passage between blades 1 and 2.

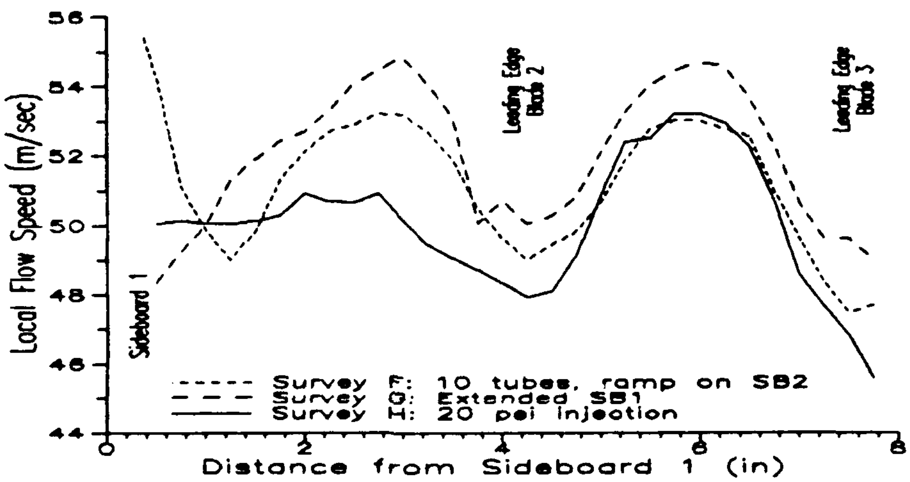


Figure 5.5 Detail of Entrance Velocity Profiles

The departure from symmetrical velocity profile in front of blade 2 with secondary injection indicates a change in the static pressure distribution on the blade surface, and hence a change in the location of the leading edge stagnation point.

5.1.2 *Effect of the Jet Grid on Turbulence*

The insertion of the grid and the addition of secondary flow significantly altered the turbulence intensity and the two turbulence scales at the cascade entrance. The data depicted in Figures 5.6b through 5.6d was taken at location C, at the entrance of the center passage (Figure 5.6a).

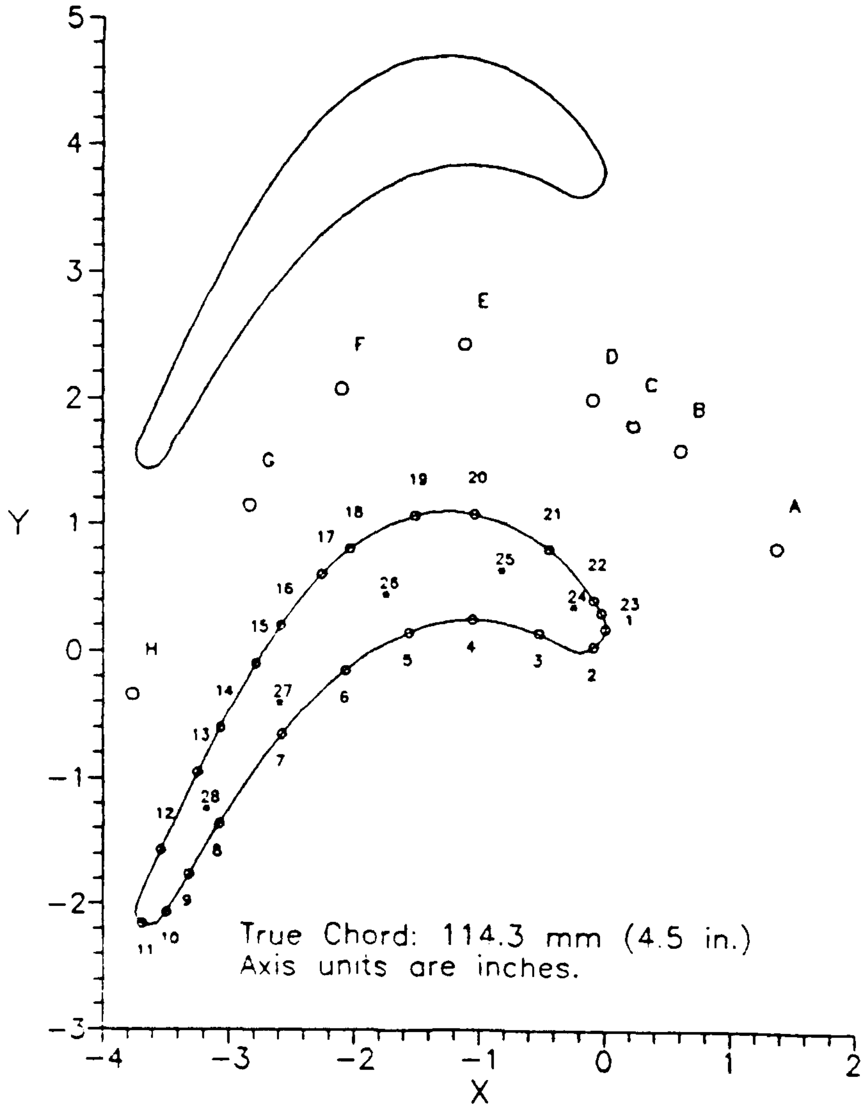


Figure 5.6a Probe Locations A Through H

As the secondary injection increased, the streamwise integral scale (Figure 5.6b) remained relatively constant at about 6 mm. Turbulence intensity likewise remained constant (Figure 5.6c), except for a slight decrease above 30 psi plenum pressure. The streamwise microscale (Figure 5.6d) increased with increasing secondary injection, confirming the earlier findings for cross-flow injection (Galassi, 1989).

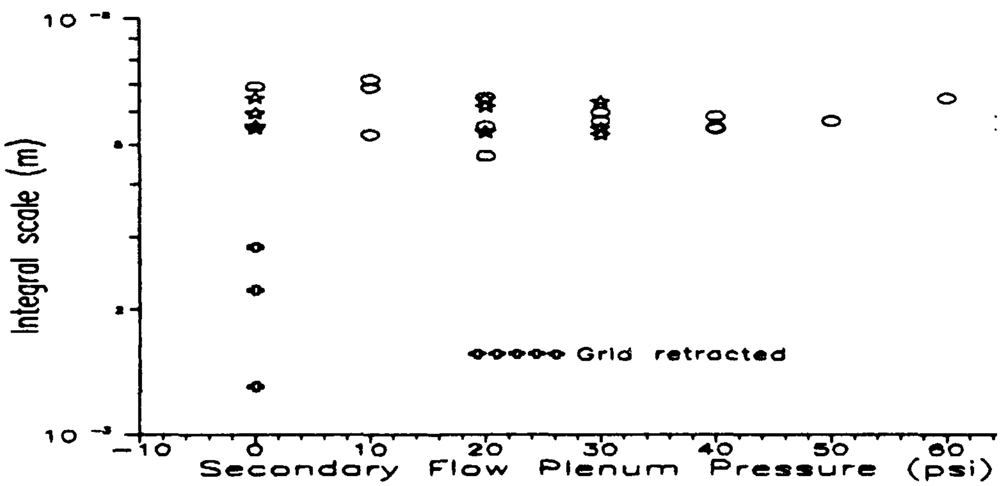


Figure 5.6b Streamwise Integral Scale Response to Secondary Flow

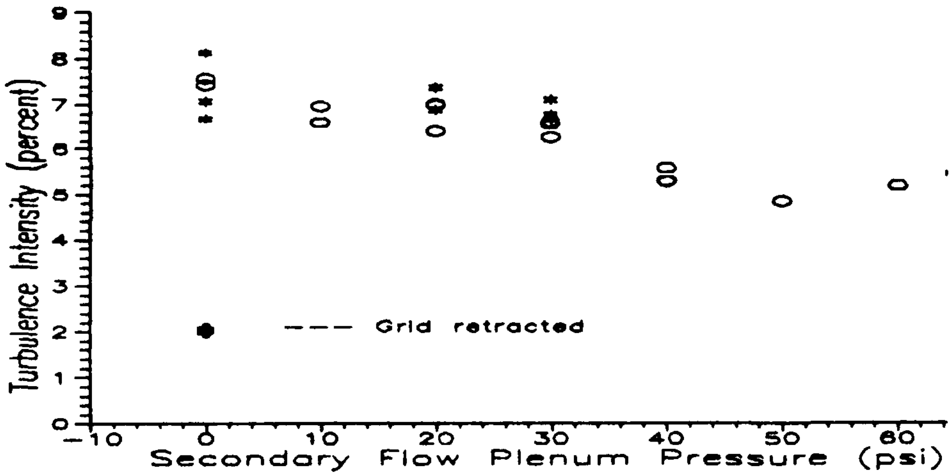


Figure 5.6c Turbulence Intensity Response to Secondary Flow

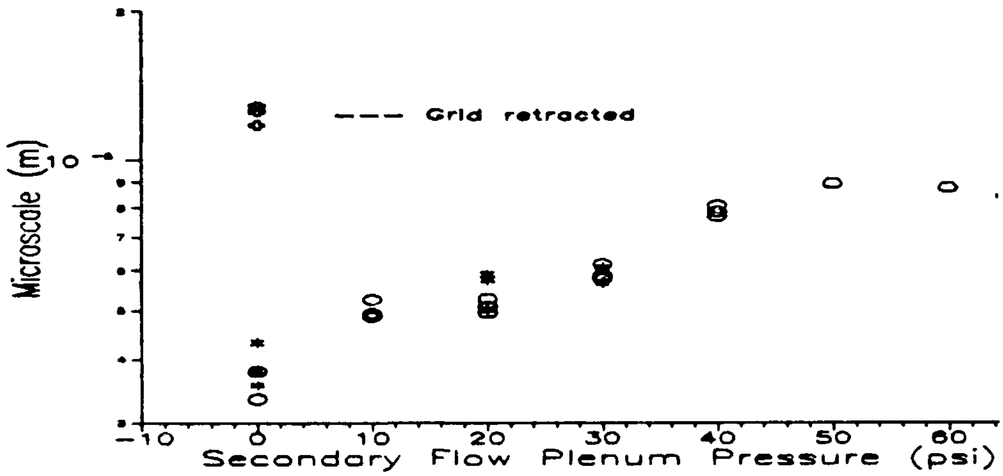


Figure 5.6d Streamwise Microscale Response to Secondary Flow

5.2 Blade Surface Flow Visualization

Flow visualization studies were made on #3 blade (Figure 3.1), both surfaces, and for the jet grid removed, followed by insertion of the grid without secondary blowing. The fan motor required a ten second wind up; this was followed by five seconds of stable flow, after which the fan motor power was cut. The fan spool down took another 30 seconds.

The titanium dioxide oil mixture worked well, and indicated that separation of the flow occurred close to the trailing edge, where the

radius of curvature sharply decreases. The suction surface vortices expanded no farther than one-fourth span from the end wall. Pressure surface vortices were even smaller. Insertion of the grid did not significantly alter the appearance of the flow patterns.

The pressure surface showed that, after initial acceleration around the blunt nose of the blade, the flow appeared to slow to near stagnation; from the infinite radius of curvature point (midway between taps 2 and 3, Figure 5.6a) to tap 7, the oil drops showed little or no movement at all. Small insects occasionally penetrated the tunnel inlet filter, and were found impacted on the pressure surfaces in this same region. After tap 7, the oil drop shape changed suddenly from circular to streaks, indicating rapid acceleration until separation between tap 10 and tap 11.

5.3 *Blade Pressure Profiles*

The pressure coefficient profiles (Figure 5.7) match well with the general shape of the Langston et al. study of the same blade profile. The profiles indicate that stagnation occurs on the leading edge in the immediate vicinity of tap #2, which is located geometrically on the pressure surface. The pressure decreases between taps 2 and 3 on the pressure side, then increases slightly from tap 3 to tap 4. This behavior is repeated consistently, grid out or in, with and without secondary flow. It indicates that the flow is initially accelerating around the blunt nose, but when the radius of curvature switches direction, an adverse pressure gradient occurs and the flow may

momentarily separate, then reattach after tap 4. The flow is nearly stagnated in this region until past tap 6. This separation bubble is significant for heat transfer, and is discussed further in Appendix E.

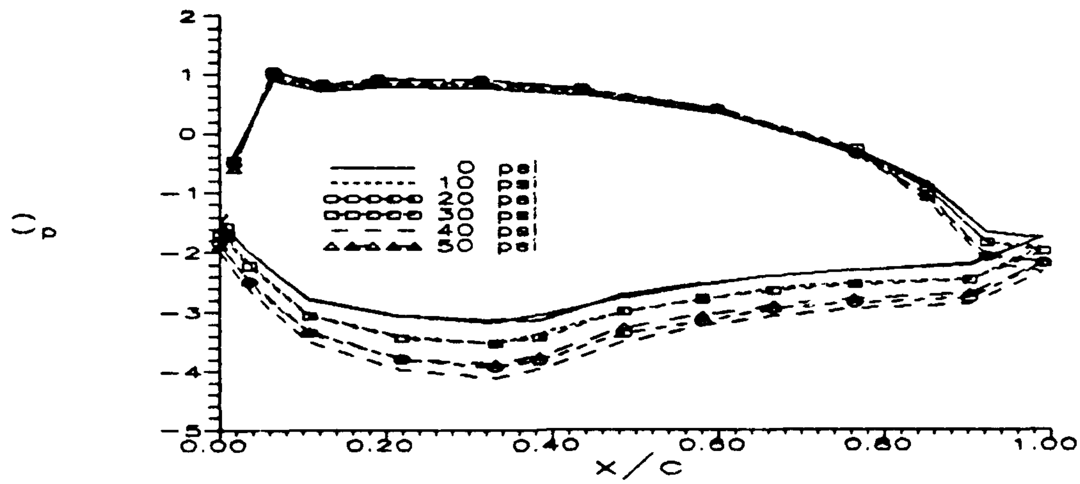


Figure 5.7 Pressure Coefficient Response to Secondary Flow

Pressure coefficients changed with insertion of the eight-tube jet grid and with the addition of secondary flow (Figure 5.7). Insertion of the grid produced slightly lower static pressures on the suction surface and the last half of the pressure surface. Addition of secondary flow caused significant alteration of the pressure profiles. The greatest changes appeared on the suction surface, and on the

last third of the pressure surface. These changes were in the form of lower static pressures, indicating higher freestream speed and higher Reynolds number. The pressure coefficients on the pressure side, between taps 2 and 6, are also higher (more stagnated) than without secondary flow.

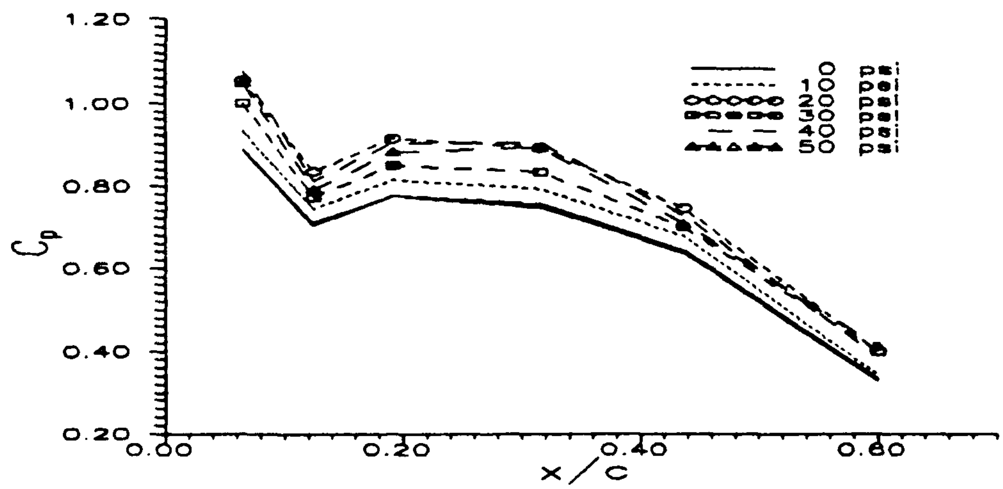


Figure 5.8a Pressure Coefficient Response Detail - Pressure Side

The shift of the pressure coefficient profile (Figure 5.7) with increased secondary flow implies that the location of the leading edge stagnation point is moving. Figures 5.8a and 5.8b are details of the pressure coefficient behavior with increasing secondary injection.

The changes in the pressure coefficient are not proportional to increasing secondary flow; the pressure coefficients increase, then decrease, then increase in magnitude as secondary flow increases.

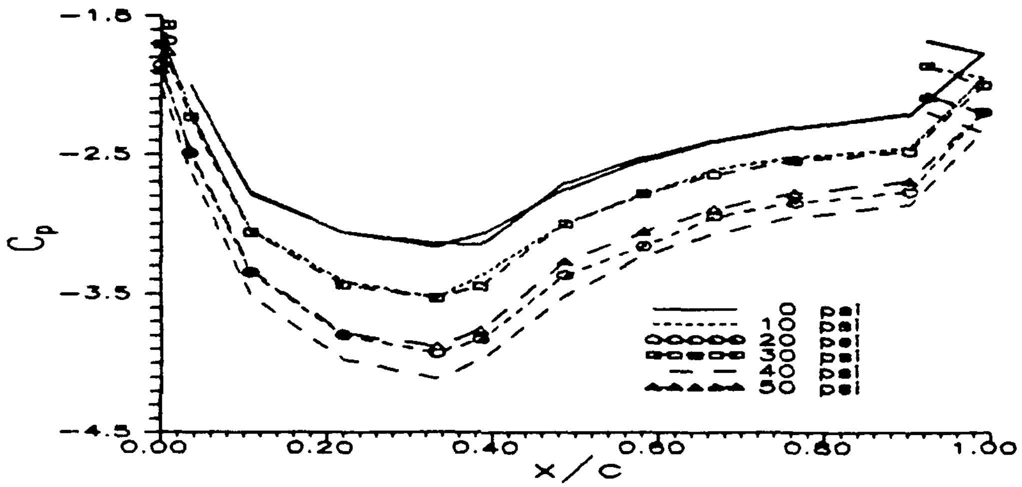


Figure 5.8b Pressure Coefficient Response Detail - Suction Side

The mechanism connecting the increase in secondary flow to changes in the pressure coefficient profile was determined to be the departure from uniform inlet velocity profile. The cause lies in the arrangement of the jet grid tubes across the primary flow. While the central core of the primary flow is subjected to the blocking effect of the grid, the area between the inlet sideboards and the outer grid

tubes may present a region of reduced resistance to the primary flow. In this case, the flow emerges from the grid location with swirl; the flow speed nearer the sideboards larger than the flow speed at the geometric center of the cascade inlet.

This departure from a uniform inlet velocity profile would produce an decreased angle of incidence on blade 2 but a increased angle of incidence on blade 3. Flow angle at the inlet to the passage between blades 2 and 3 (probe location C, Figure 5.6a) may show erratic or no change at all. The erratic behavior of the pressure coefficients on both suction and pressure surfaces indicates instability of the inlet pressure field as secondary injection increases.

Also, for the above case, the pitot-static tube would measure a lower q than the stagnation point on blade 2. The location of the tube during the tests was 53 mm away from sideboard 1 (Figure 3.1), well removed from the accelerated flow "leaking" between the jet-grid device and the sideboard. It would measure the q in a region of slightly slower than average speed, due to the variable blocking effect of the jet-grid. Increasing secondary flow would increase the blocking effect, reducing the dynamic pressure at this location: this effect was confirmed during a pitot-static tube survey. Because this dynamic pressure was used for pressure coefficient computation, this effect introduced increasing error into all the pressure coefficients with increasing secondary flow, in the form of (slightly) overstating (reporting larger than actual values) the actual pressure coefficients.

Overstated pressure coefficient means overstated local velocity, and therefore local Reynolds number, on the blade. The errors are introduced with insertion of the grid, and increase (up to a point) with increasing secondary flow pressure.

The erratic behavior of the pressure coefficients for the eight-tube grid, and the departure from symmetrical entrance velocity profile for the ten-tube grid, show that secondary flow changes the pressure field around the blade. This implies movement of the leading edge stagnation point and changes in the angle of incidence. Since both the angle of incidence and the local velocities were affected, the heat transfer study was invalidated as far as comparison between different levels of secondary injection. A detailed discussion and error analysis appear in Appendix E.

5.4 *Passage Flow Behavior*

The passage turbulence investigation was performed with the ten tube jet grid at 20 psi plenum pressure. The fifteen selected probe locations within the center passage are depicted in Figure 5.9. At each location, three scans were recorded, then reduced to velocity and turbulence parameters.

The results are depicted on the graphs against nondimensional distance through the passage (l/c), in terms of flow path location: near the suction surface (circles), passage center (squares), and near the pressure surface (triangles). The streamwise and normal component parameters are further differentiated where appropriate by dark

symbols (streamwise) and open symbols (normal). Bands connecting the symbols indicate the general trend while giving a sense of the repeatability (band width) of the measurement. Only two scans out of fifteen failed to reduce to velocity information; these were at the same location near the pressure side, where only one triangle data point is shown.

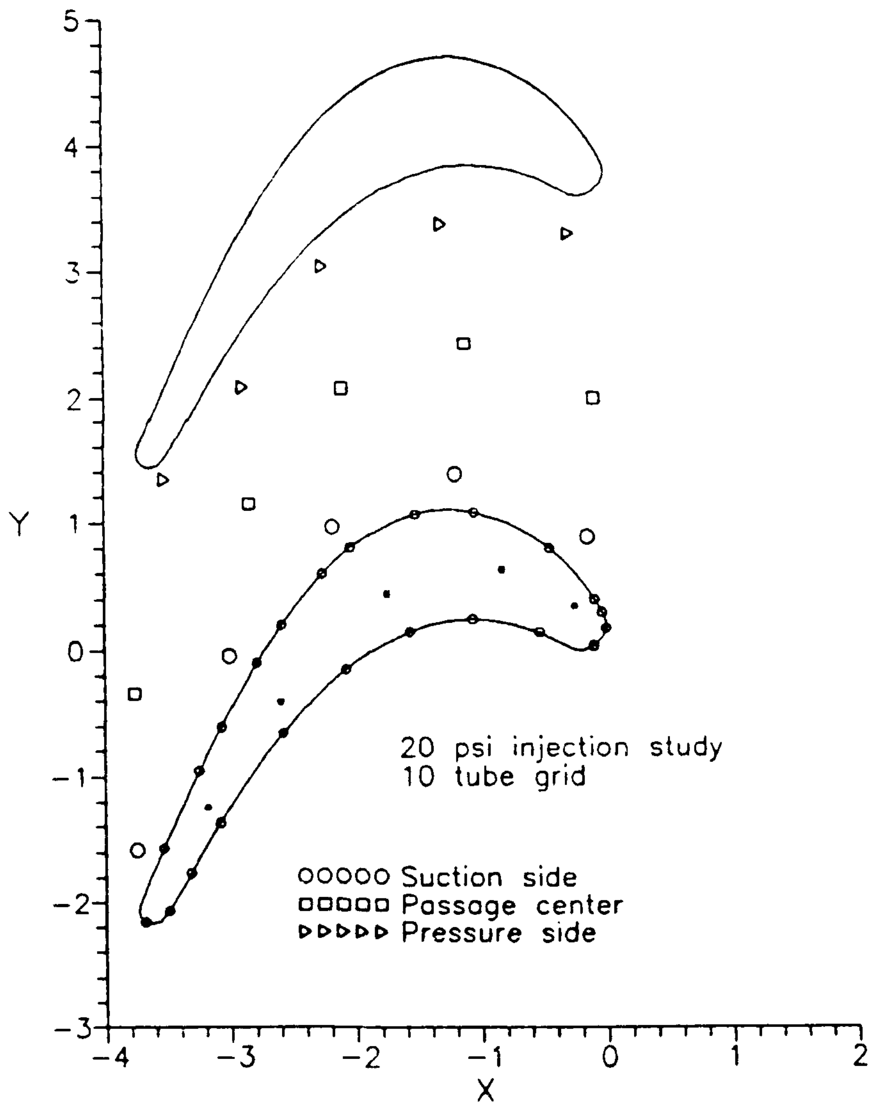


Figure 5.9 Probe Locations for Passage Flow Study

Local speed (U_∞) is depicted for the fifteen locations in Figure 5.10, and consolidated turbulence intensity (Tu, Equation 2.2) is depicted in Figure 5.11. Figure 5.12 shows the relative size of the integral turbulence scales. These three figures will be referenced again as each flow path is discussed in turn.

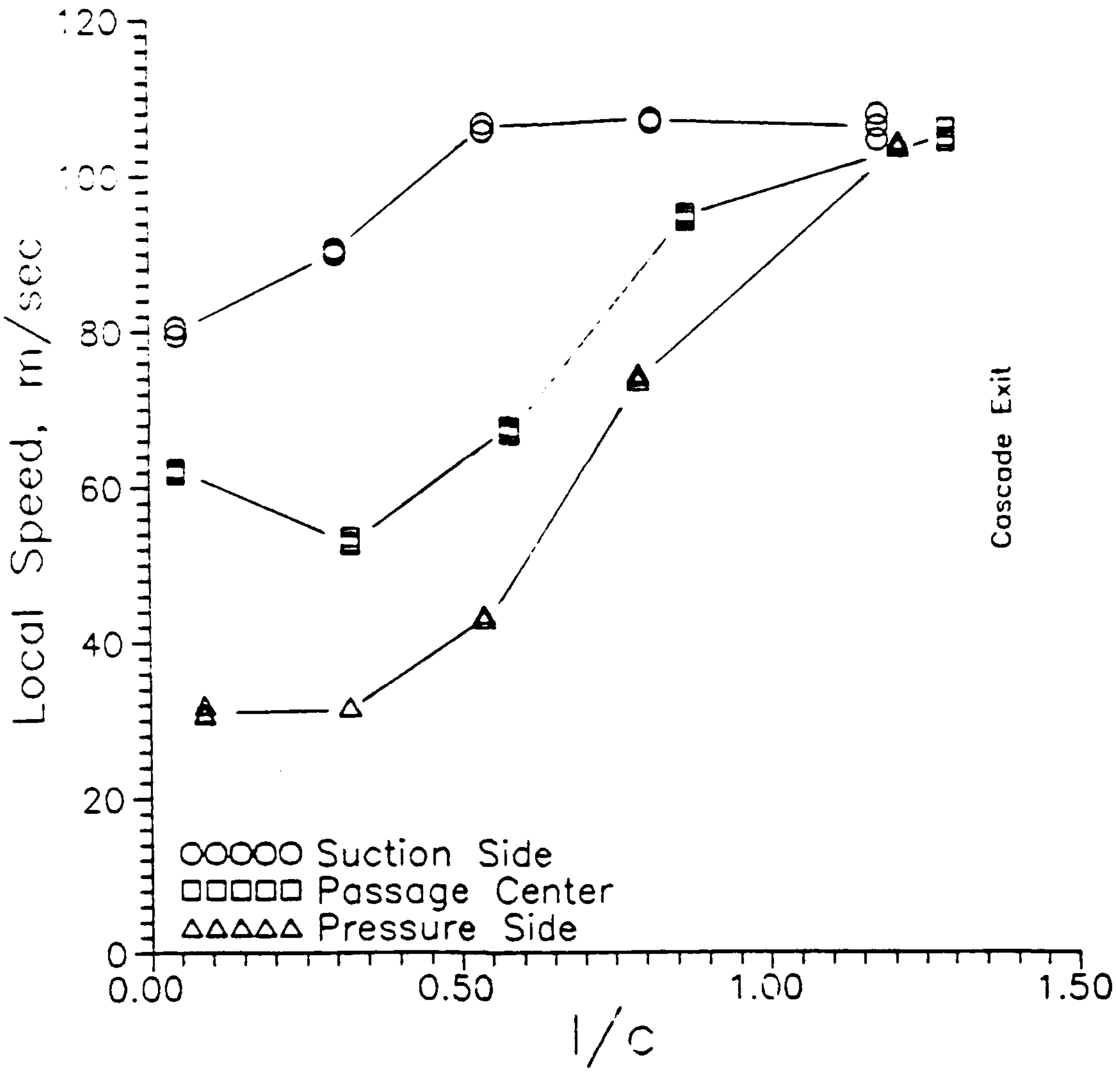


Figure 5.10 Passage Flow Speed

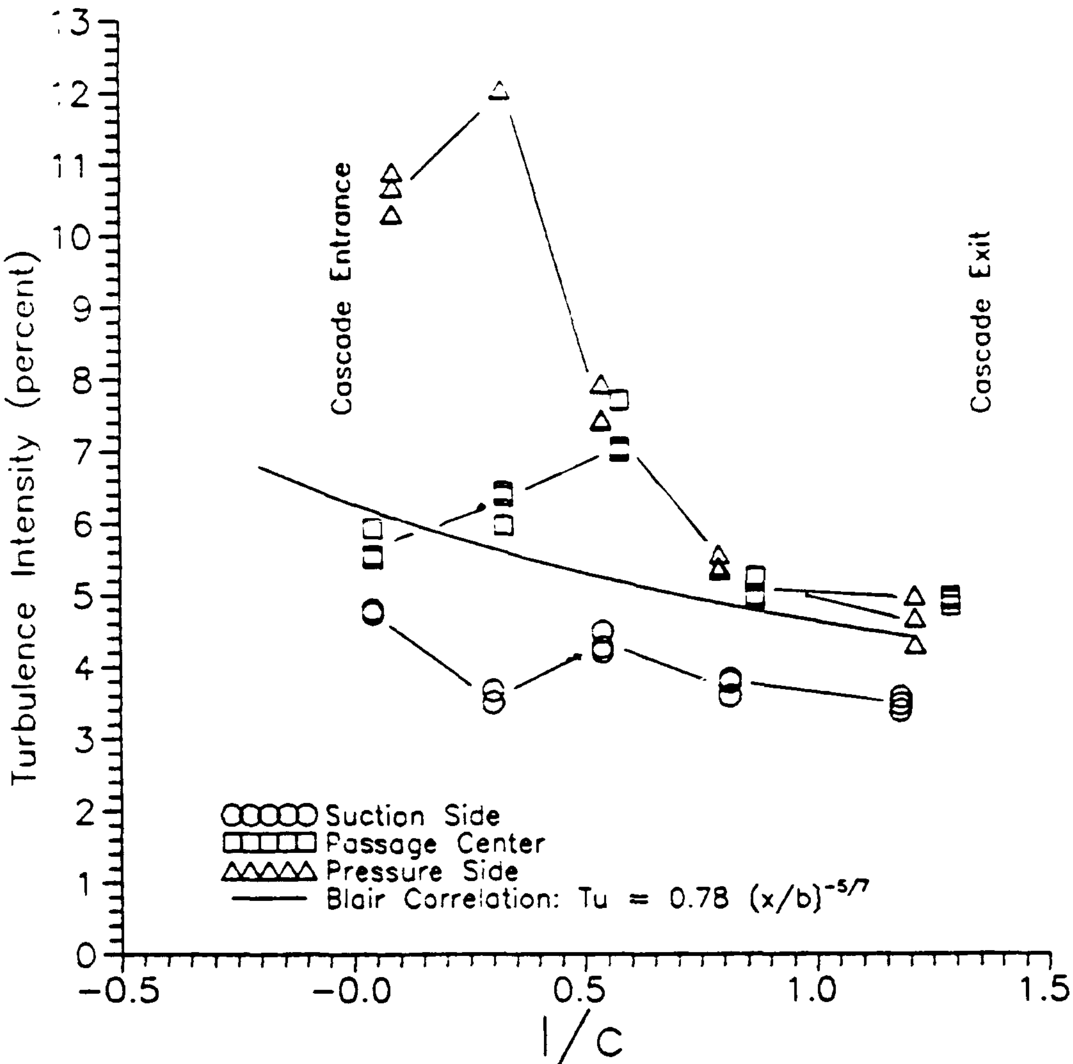


Figure 5.11 Passage Turbulence Intensity

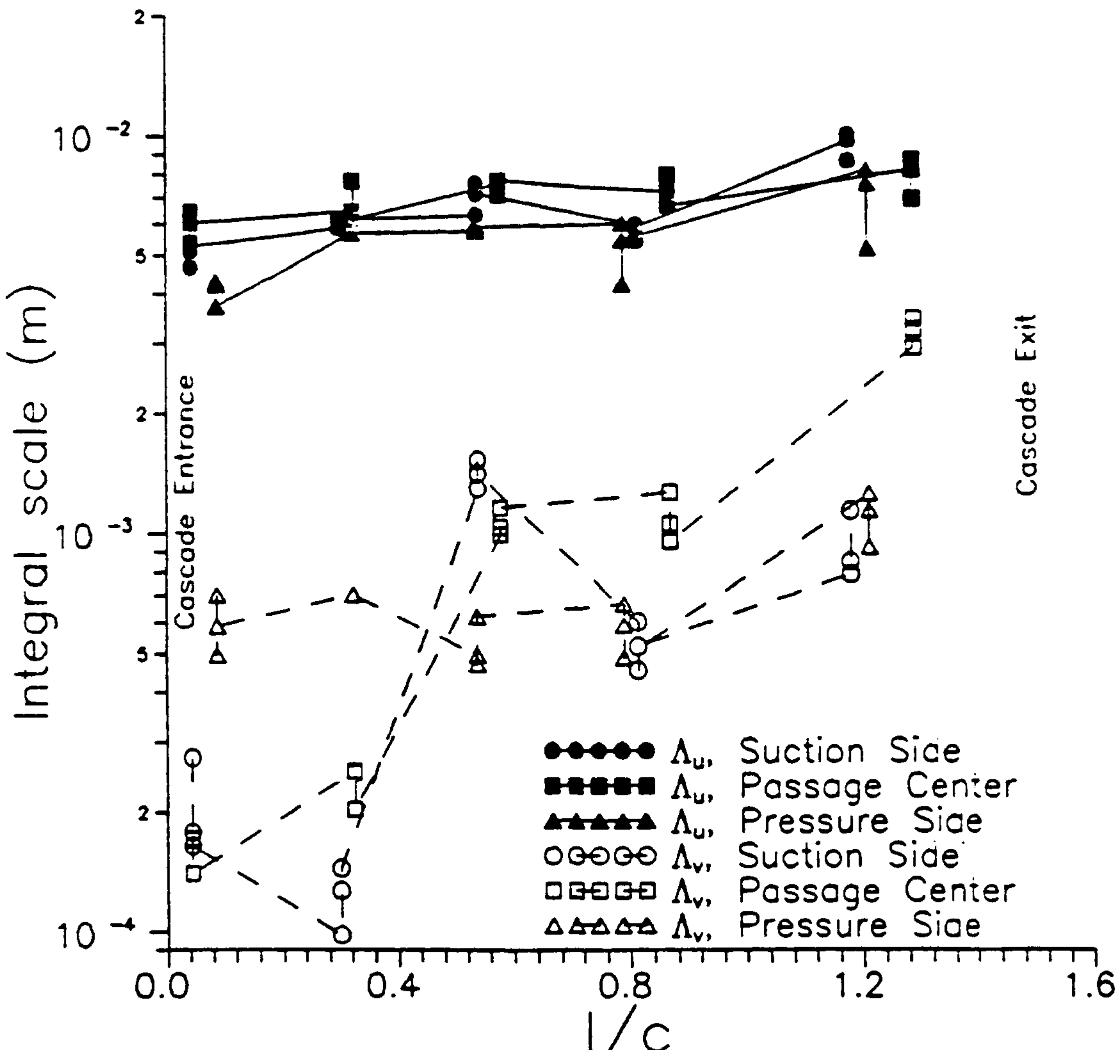


Figure 5.12 Passage Integral Scale Behavior

Figure 5.13 depicts the relative size of the microscales in the passage. Figures 5.14 and 5.15 illustrate the relative magnitudes of the two components of turbulent energy dissipation (Equation 2.17) through the passage. The data in these three figures is depicted separately for the suction surface, passage center, and pressure surface flow discussions that follow.

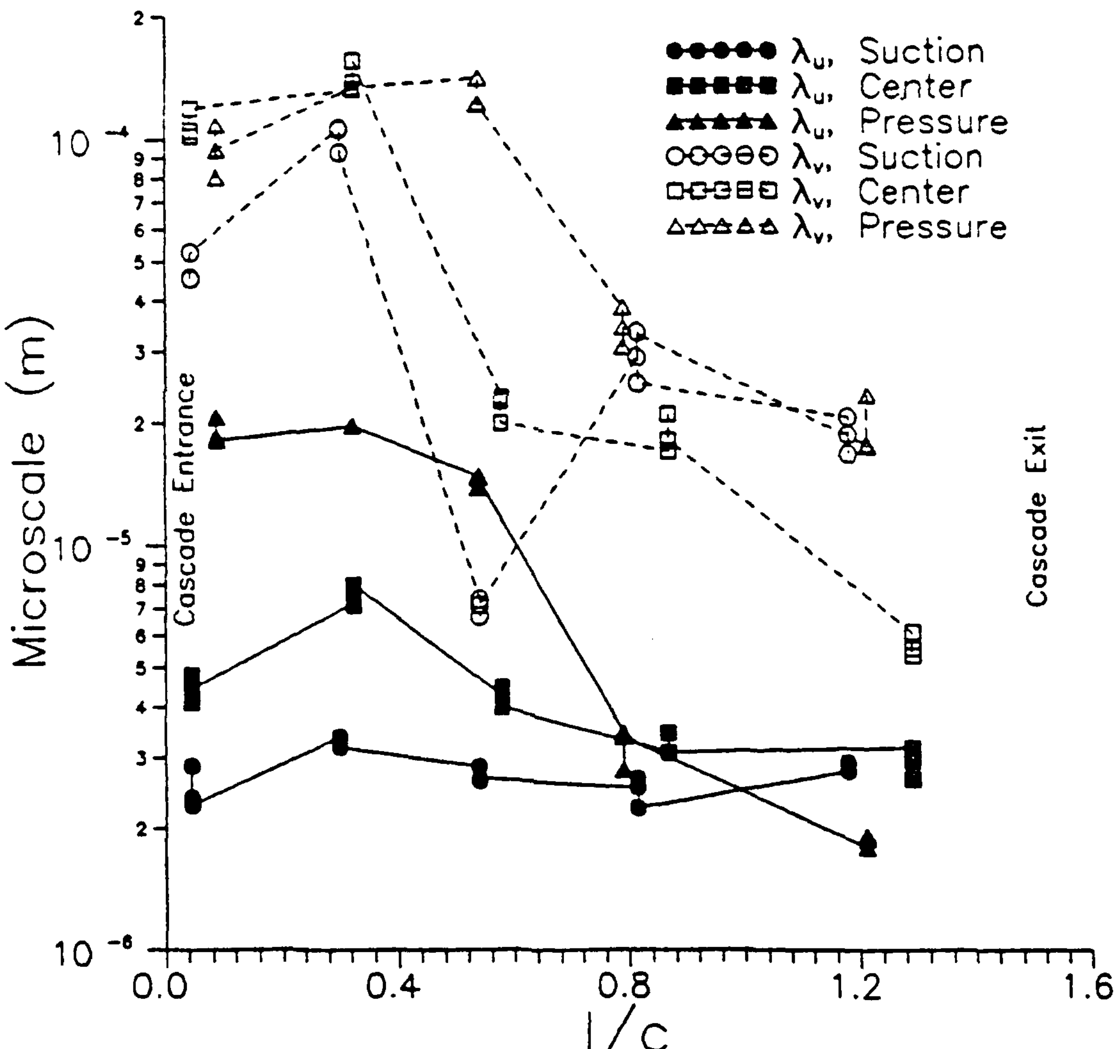


Figure 5.13 Passage Microscale Behavior

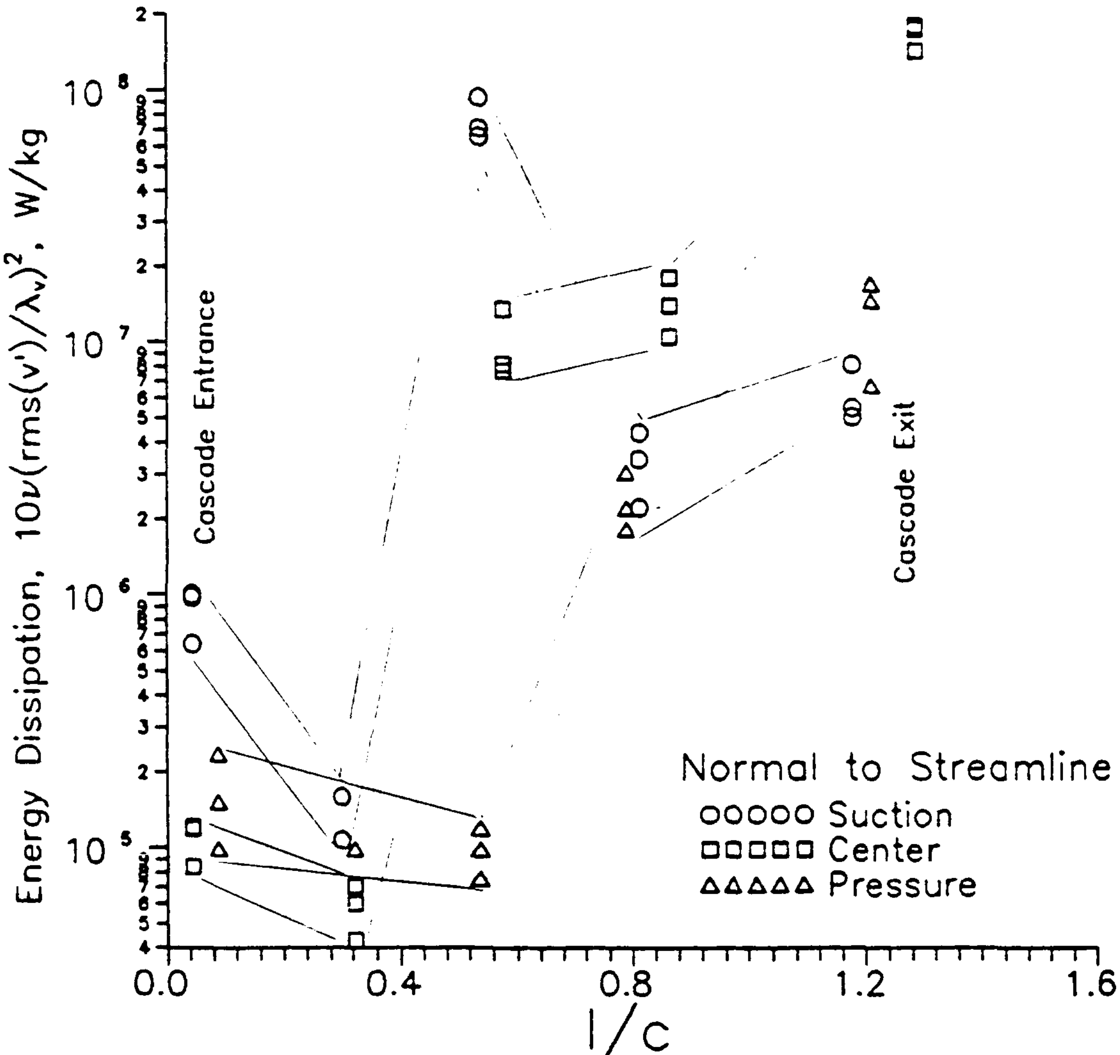


Figure 5.14 Normal Kinetic Energy Dissipation

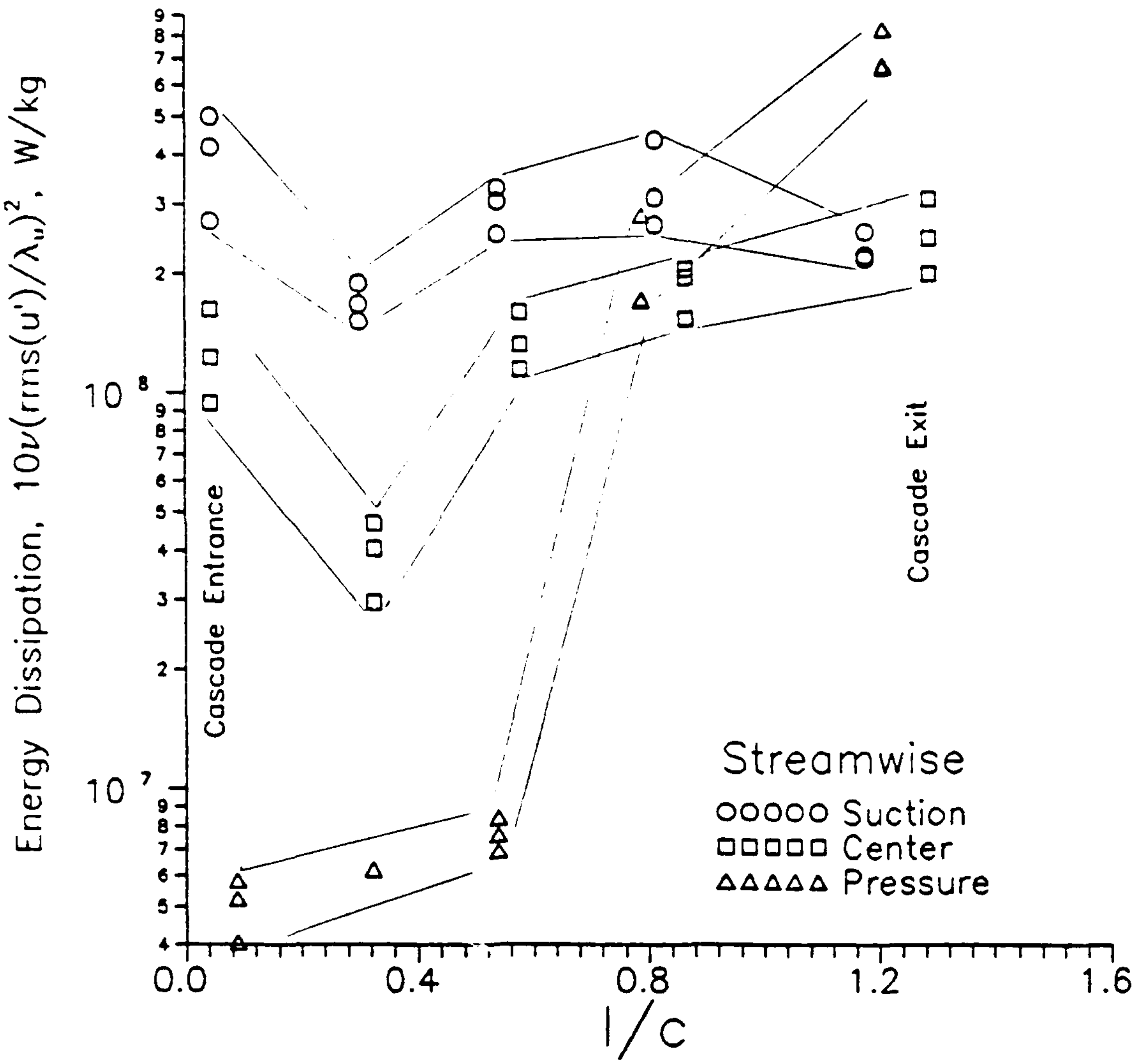


Figure 5.15 Steamwise Kinetic Energy Dissipation

5.4.1 Suction Surface

The point of measurement nearest the entrance for the suction surface flow shows the flow is already strongly accelerated (Figure 5.10). The flow continues to increase speed until about 50% chord, then remains constant to the exit. The streamwise (u) velocity fluctuations are fairly constant during this process (Figure 5.16), which matches the findings in a similar cascade (Priddy and Bayley, 1988:77). However, the normal component (v) perturbations increase suddenly above the streamwise values, then converge back as the flow approaches the cascade exit, where they are equal, indicating turbulence isotropicity.

The integral scale matches the trends in the fluctuations in both components (Figure 5.12), but the eddies retain an elliptic shape oriented with the streamlines. The streamwise microscale λ_u (Figure 5.17) remains constant at the smallest recorded level in the passage (20 microns), with the normal microscale λ_v decreasing by a factor of ten, then increasing (Figure 5.17). The small λ_u means high frequencies are present which rapidly dissipate energy.

The normal energy dissipation rate $\dot{e}_v$ begins low, then rapidly approaches the nearly constant streamwise value of 300 MW/kg (Figure 5.18). This enormous dissipation rate $\dot{e}_u$ must be balanced by the production, diffusion, and other terms in the turbulent kinetic energy equation (Cebeci and Smith, 1974). The fact that this high rate (exceeded only briefly near the pressure side, Fig-

ure 5.15) is sustained throughout the passage indicates that either the production term or the pressure work term (or their sum) must be even larger than the diffusion term. The cause of the sudden pulse appearing in the v parameters (v', λ_v, $\dot{e}_v$) is not clear.

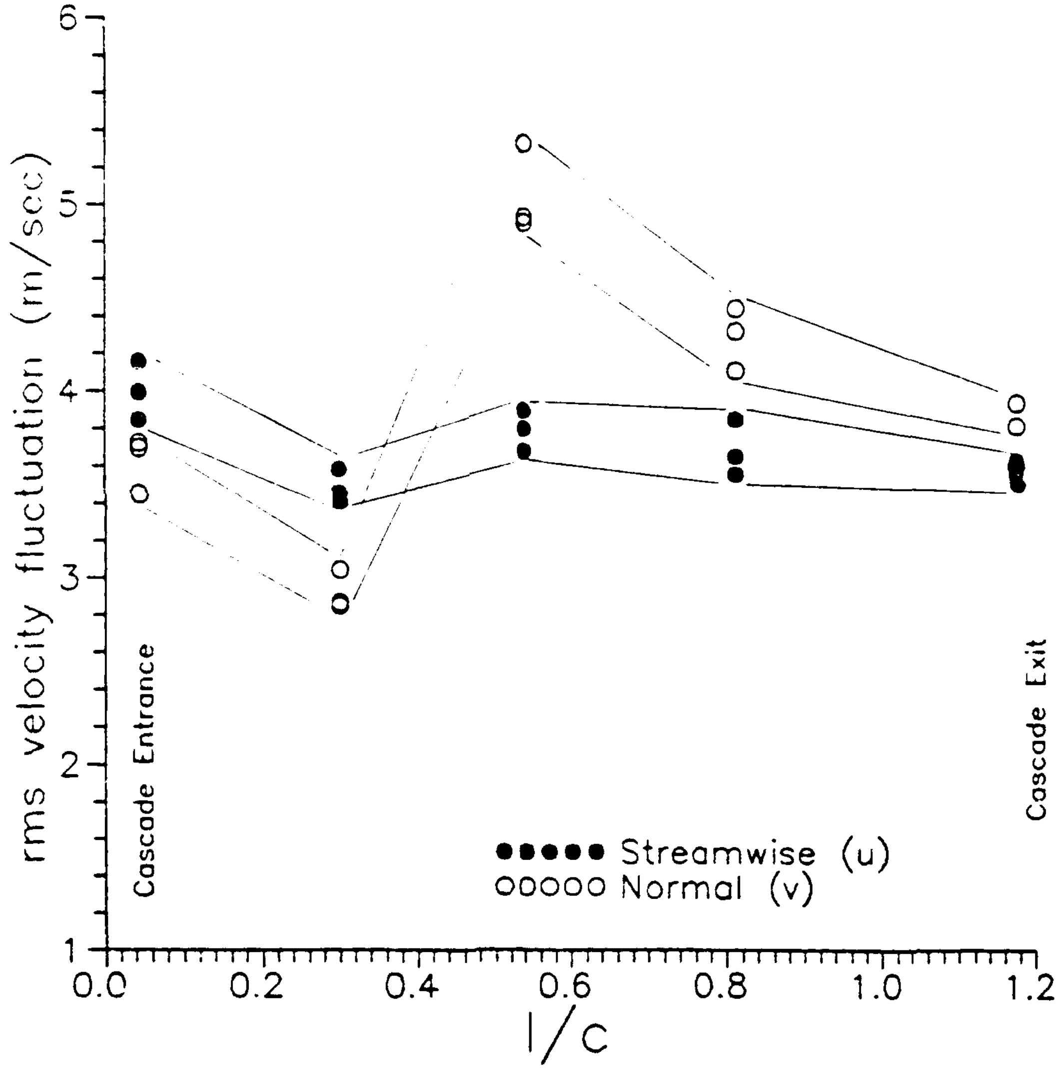


Figure 5.16 Suction Side Velocity Fluctuation

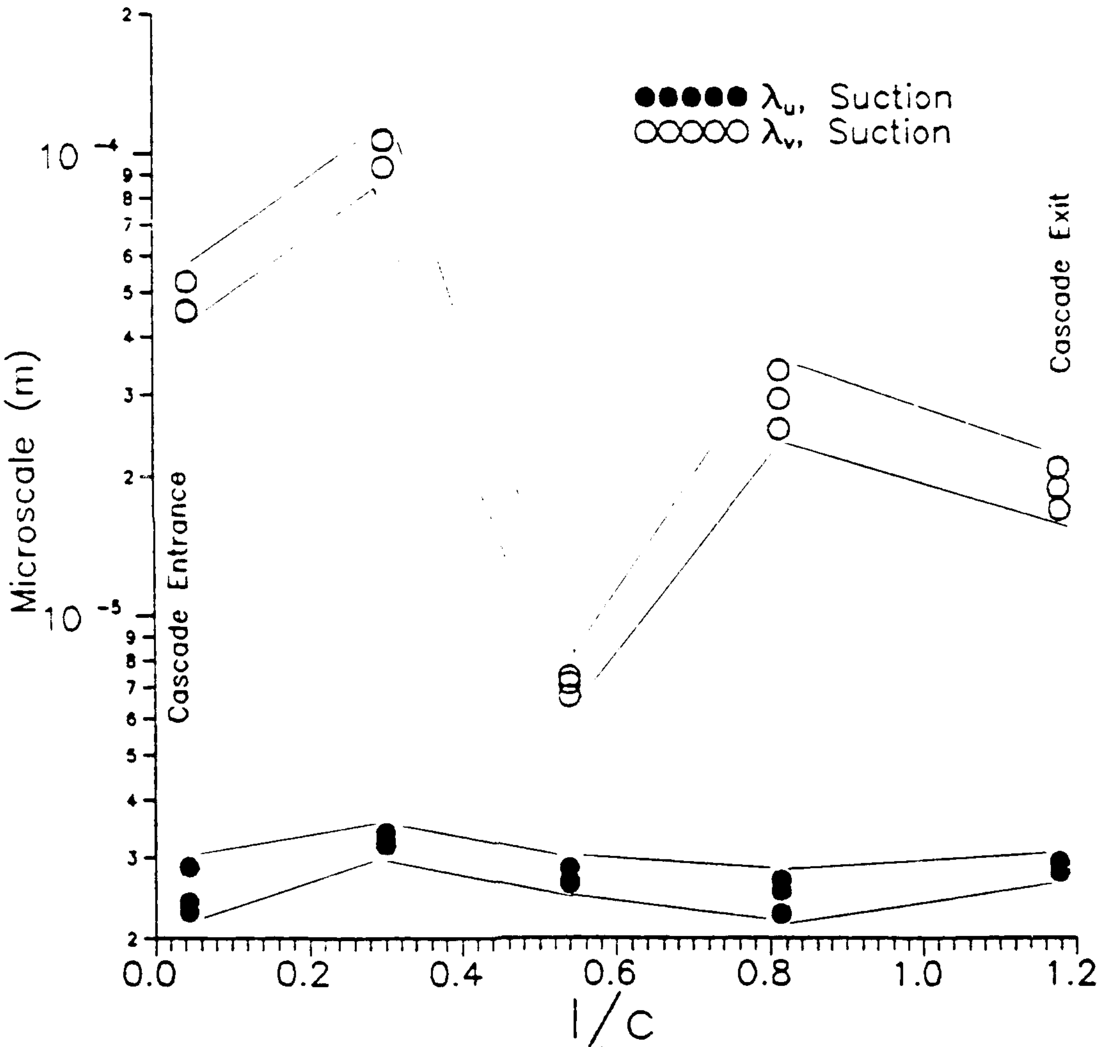


Figure 5.17 Suction Side Microscale

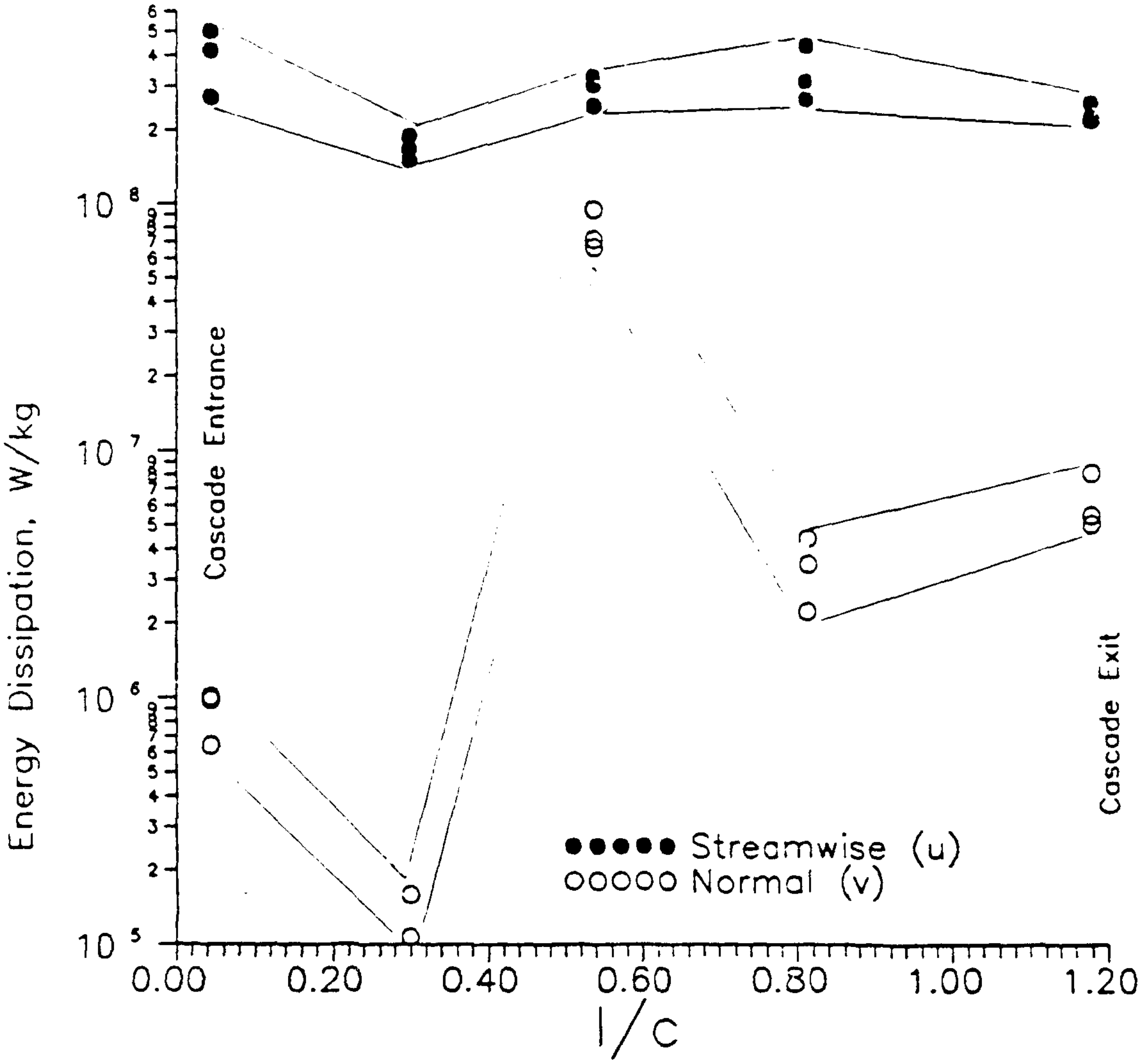


Figure 5.18 Suction Side Energy Dissipation

5.4.2 Passage Center

Turbulence intensity in the passage center (for the streamwise component alone) has been measured in a three blade turbine cascade using LDA equipment (Priddy and Bayley, 1988). These studies indicate a monotonic decrease of turbulence intensity in the passage center, and nearly constant values across the exit plane of the passage. The amplitude of the velocity fluctuations (u') were found to remain relatively constant through the passage. The present study confirmed the constant streamwise fluctuation (Figure 5.19), but this is accompanied by a strong jump in the normal (v') fluctuation level, similar to the suction surface results (Figure 5.16). Accordingly, the turbulence intensity (a function of both components) does not decrease monotonically (Figure 5.11), but first increases nearly 2%, then drops. This is partly driven by a slight deceleration on passage entry (Figure 5.10), but the primary cause is the increased v perturbations.

The passage center streamwise integral scale component (Figure 5.12) increases slightly through the passage; the normal component starts small and increases an order of magnitude. Initially both microscales exhibit slight growth indicative of normal decay (Figure 5.20). The streamwise microscale is smaller, remains small and fairly constant, while the normal microscale decreases by a factor of 100. Energy dissipation (Figure 5.21) slightly decreases (as in turbulence decay), then increases in both components until

reaching the same level in both (10^8 W/kg) as the flow exits the cascade (Figure 5.21). The dissipation is dominated by the stream-wise component until the cascade exit, where the two components are equal.

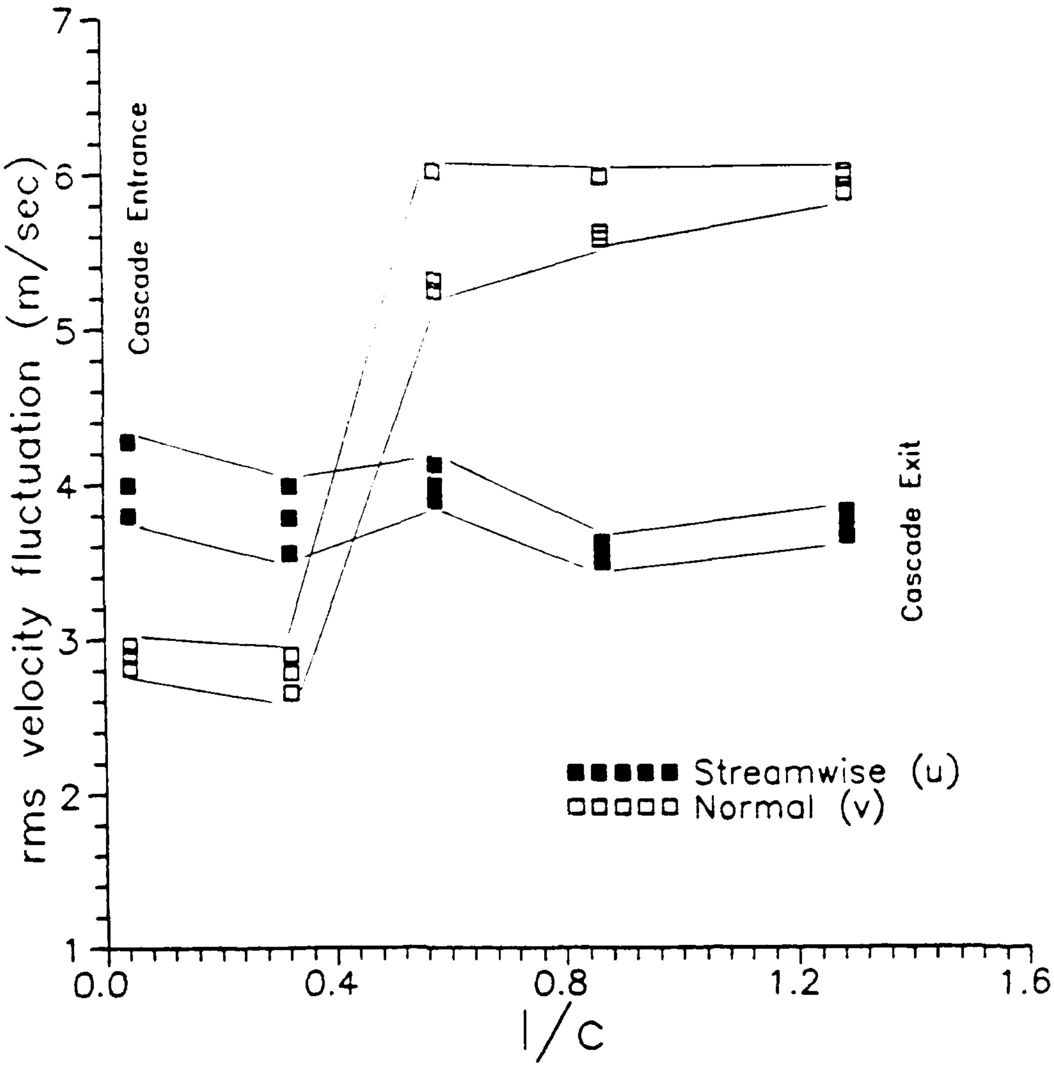


Figure 5.19 Passage Center Velocity Fluctuation

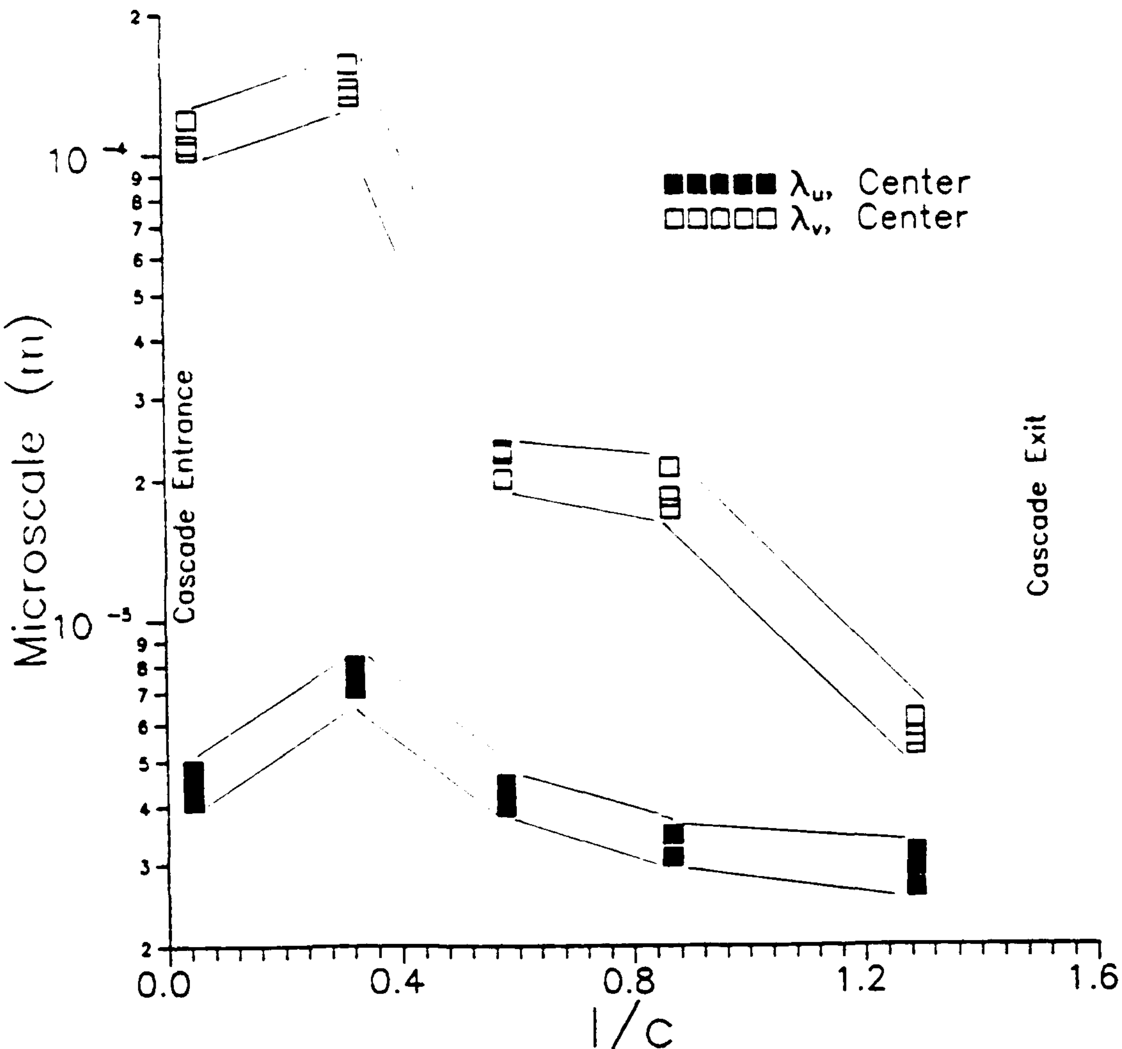


Figure 5.20 Passage Center Microscale

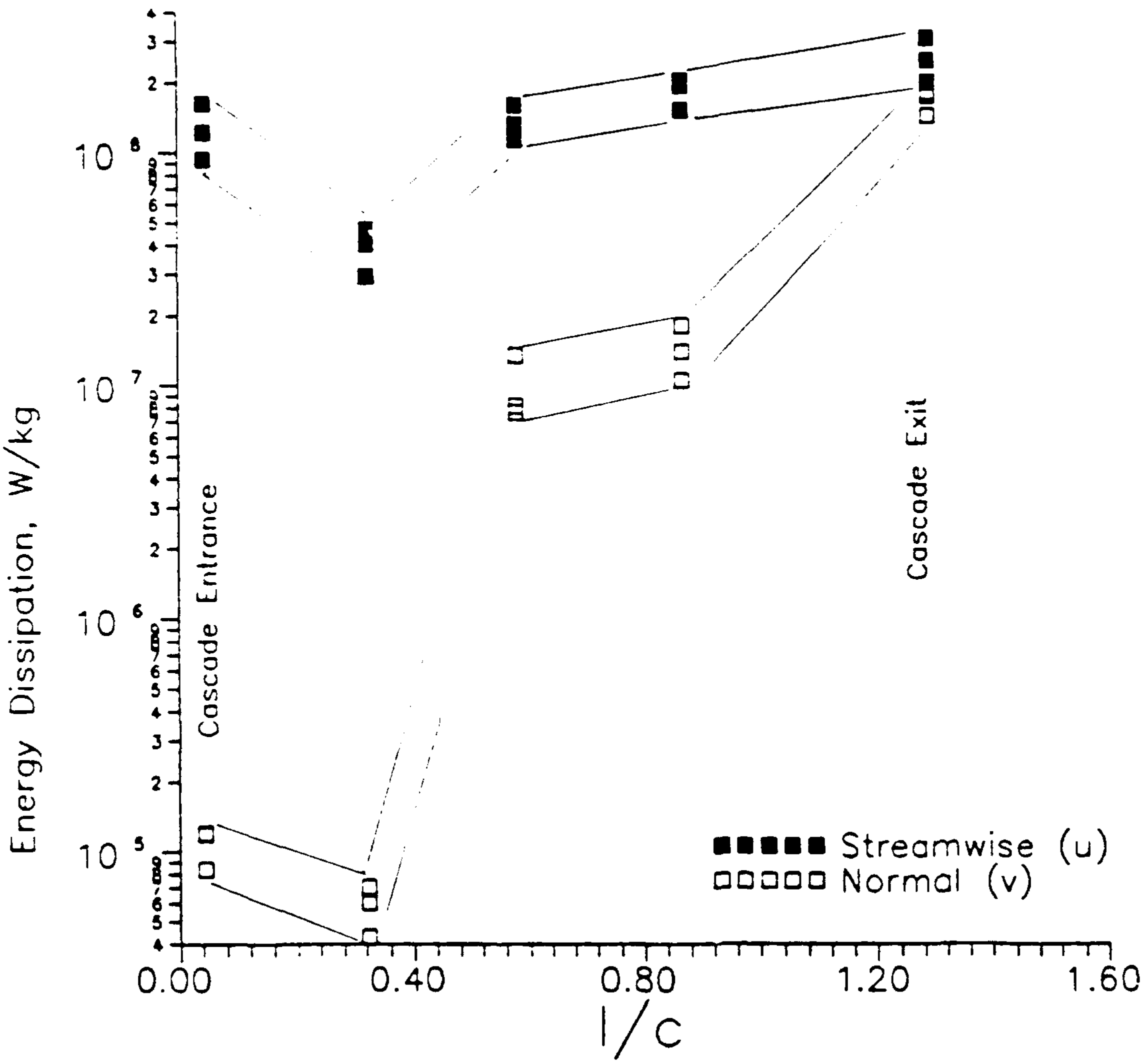


Figure 5.21 Passage Center Energy Dissipation

The nearly constant small λ_s (Figure 5.20) indicates that turbulent energy is arriving/being generated early in the passage center. The sudden increases in v' (Figure 5.19) and $\dot{e}_v$ (Figure 5.21) indicate that a significant portion of the energy dissipating in the u direction may be diffusing into the center streamlines from the sides of the passage. The most likely source of this diffusion is the turbulent-energy-rich suction surface side of the passage. The streamwise pressure gradient is weak in the first part of the passage (weak acceleration, Figure 5.10; little change in fluctuation, Figure 5.19), but the normal pressure gradient is very strong, shown by the pressure coefficient distribution (Figure 5.7). This strong normal gradient may be causing the pressure work term to become large, or may act as an amplifier for the normal diffusion process.

5.4.3 Pressure Surface

Flow near the pressure surface enters at low speed (Figure 5.10), with nearly identical fluctuation components (Figure 5.22), resulting in high turbulence intensities (greater than 12%, Figure 5.11). Two out of three scans failed at the second point; it is likely that the flow vector momentarily aligned with one of the hot wires, as described before. The flow begins to accelerate about mid passage (Figure 5.10), picking up increased normal and streamwise velocity perturbations (Figure 5.22). The net effect, however, is a rapid decrease in turbulence intensity (Figure 5.11).

The integral scales both remain relatively fixed (Figure 5.12). The microscales also remain relatively level (Figure 5.23) until the strong acceleration begins, then both decrease together. The energy dissipation rates (Figure 5.24) in both components also react in concert, the ϵ_u increasing a hundredfold to reach the highest rate measured (800 MW/kg, Figure 5.24).

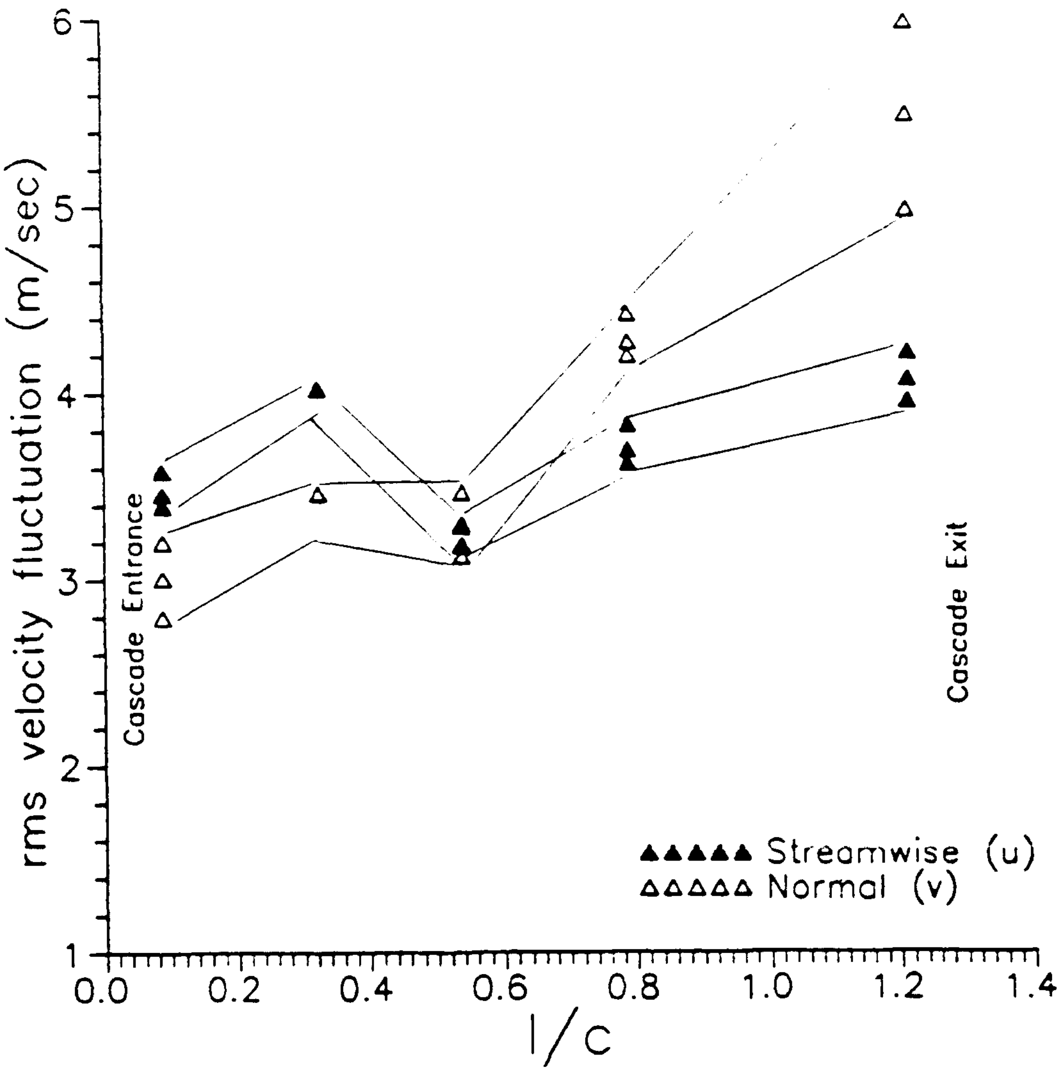


Figure 5.22 Pressure Side Velocity Fluctuation

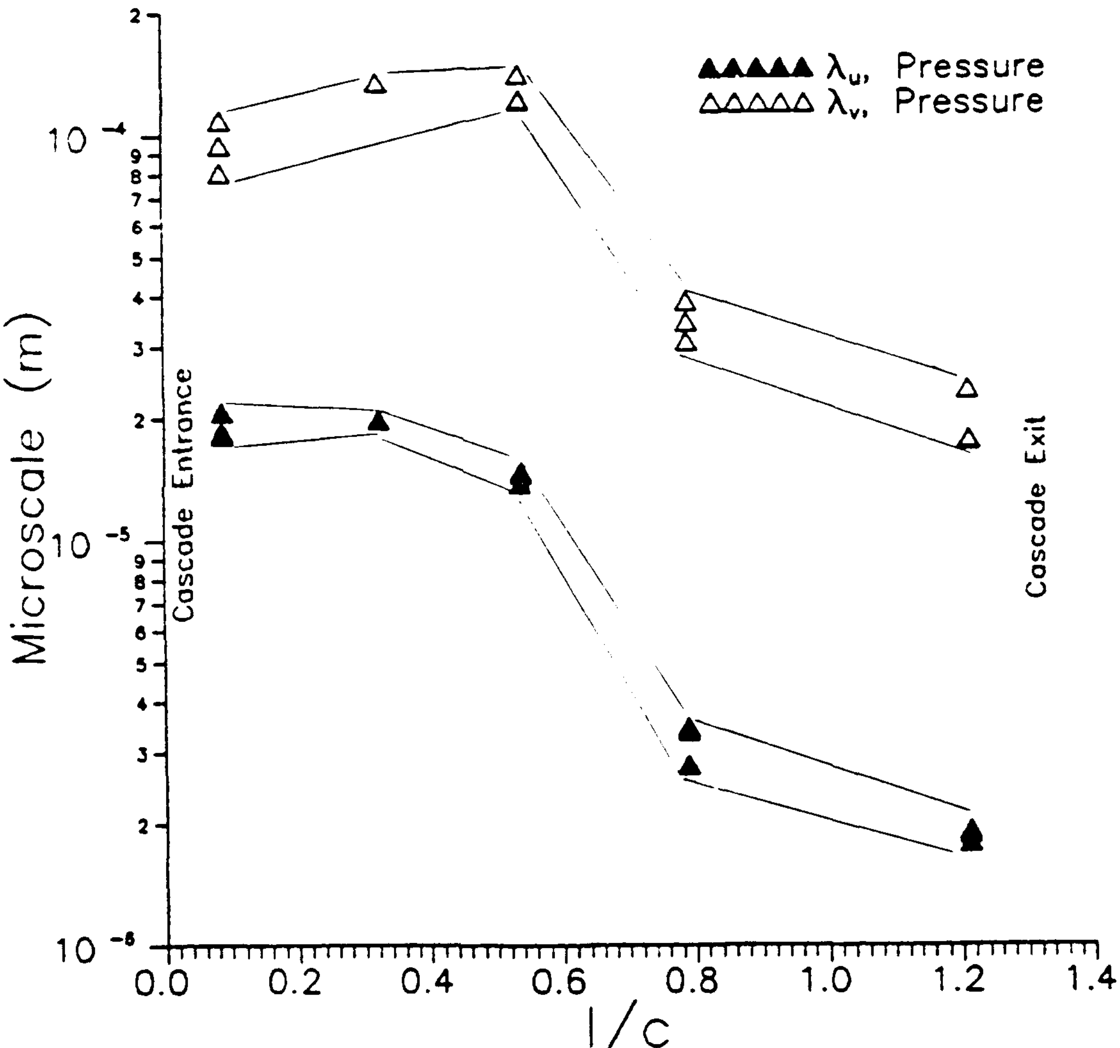


Figure 5.23 Pressure Side Microscale

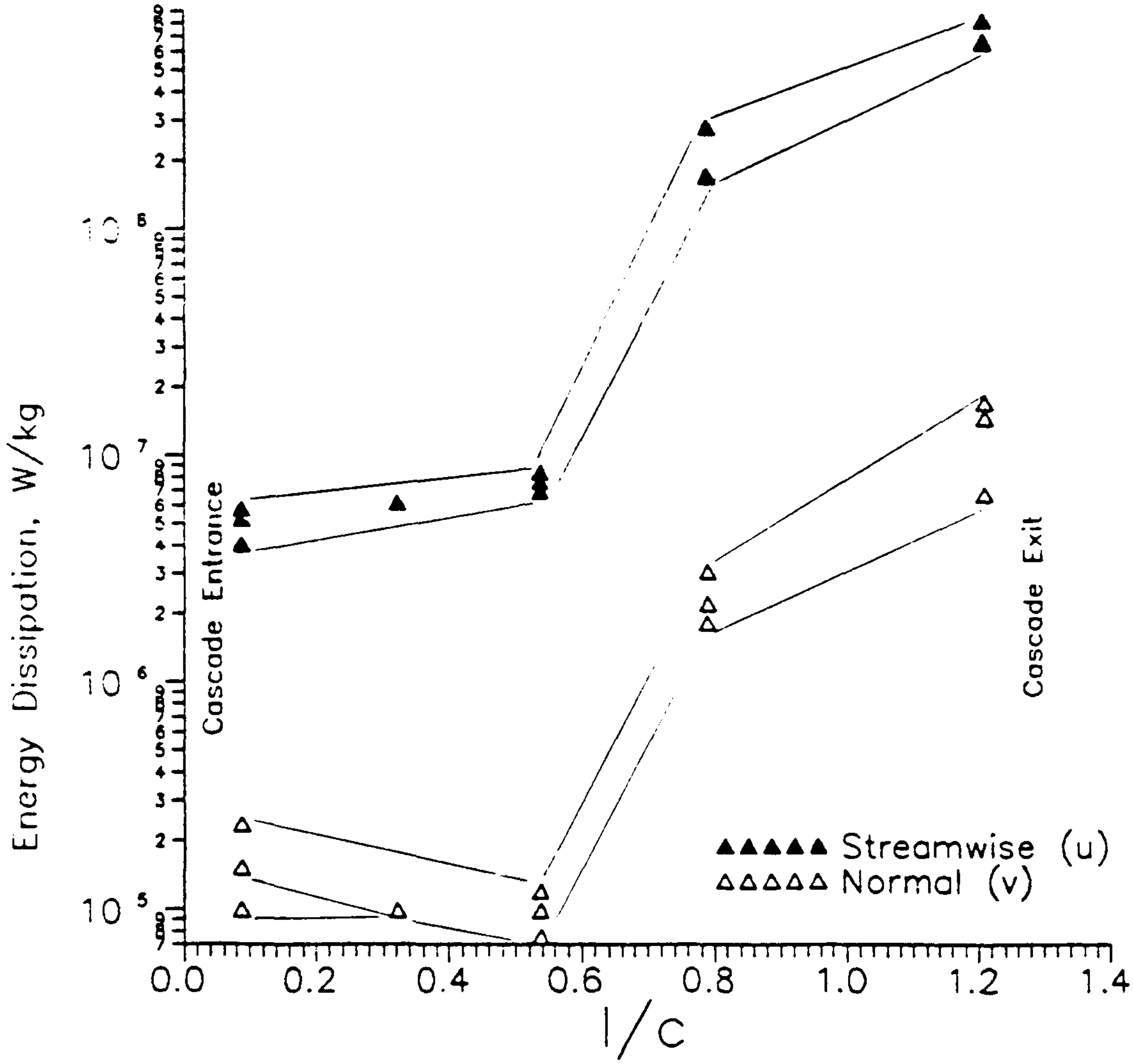


Figure 5.24 Pressure Side Energy Dissipation

This parallel behavior between the u and v components of microscale and energy dissipation does not occur elsewhere in the passage. In both center and suction side flow, the u and v microscales behave as if they were completely independent. The

corresponding energy dissipation rates are similarly independent. The dramatic increase in the energy dissipation for the pressure side is disguised in Figure 5.24 by the logarithmic scale: it amounts to a steady explosion, a hundredfold increase in both u and v components.

The dominant macroscopic characteristics for this region are the large streamwise pressure gradient and accompanying acceleration. These two do not necessarily produce turbulent energy. The proximity of the flow in this region of the passage to the separation bubble, an unstable flow feature, and the lack of a stabilizing boundary (the wall) may cause the free-stream acceleration to proceed in chaotic, rather than orderly, fashion.

5.4.4 Summary of Passage Flow Behavior

Dramatic changes in the normal velocity component fluctuations indicate that this is an essential key to understanding the diffusion of turbulent energy into the free stream from the suction surface boundary layer. Changes in the energy dissipation rates indicate that the passage center is influenced early by turbulent events near the suction surface.

Later in the passage, increasing normal velocity fluctuations near the pressure surface coincide with sharp increases in energy dissipation and decreasing microscale. This sudden development is reflected by further increases in the center flow dissipation rates, which now appear to be responding primarily to events on the pressure side. Again, the v' appears to be the principal diffusion vehicle. It appears that the turbulent kinetic energy originating near the pressure side appears first in the streamwise center dissipation rate, which is immediately transmitted into the normal component, so that the center v dissipation rate exceeds both pressure and suction v dissipation rates as the flow exits the cascade. The immediate $\dot{e}_v$ response to the u component increase is due to the large v'.

Table 5.1. Summary of Passage Flow Trends

Characteristic	Suction Side	Passage Center	Pressure Side
u'	slight decrease	constant	slight increase
v'	sudden increase	suddenly doubles	large increase
Turbulence intensity	low, slight decrease	increases then decreases	high, rapid decrease
u integral scale	nearly constant	nearly constant	nearly constant
v integral scale	low, sud-den increase	low, contin uous increase	nearly constant
u microscale	nearly constant at small level	nearly constant at small level	large, rapid decrease
v microscale	large, sud-den decrease, then increase	large, rapid decrease	large, rapid decrease
u dissipation rate	high, nearly constant	high, nearly constant	low, rapid increase
v dissipation rate	low, sud-den increase, then decrease	low, sud-den increase	low, rapid increase

VI. Conclusions

Curiouser and curiouser.

- Alice

The jet-grid device caused a significant departure from uniform inlet velocity profile, so that the dynamic pressure measured behind the grid was less than the average dynamic pressure, and the angle of incidence on blade 2 became a function of secondary injection velocity.

In this attempt to change a microscopic parameter (the microscale), a change in a macroscopic parameter (angle of incidence) resulted, which undermined much of the effort. At this point, no definitive statements can be made about the relationship between surface heat transfer and the microscale parameter. This study neither confirms nor denies that such a relationship exists, nor does it indicate the possible order of the microscale effect.

It is appropriate to compare the size of the microscale and the tungsten wire diameter. The smallest microscales obtained were 2 microns; the tungsten wire is 3.8 microns in diameter. The microscale is derived from a frequency distribution, not from direct measurement. The smallest microscales produced the highest energy dissipation rates. Near the suction surface, the streamwise energy dissipation rate averages 300 MW/kg; assuming this process is sustained while a fluid parcel traverses the passage (in 1/800 s), this should produce a temperature increase of about 380 degrees K. This increased temperature was not

observed, and appears unreasonable even if it affected only a small fraction of the flow. The small microscale values (i.e., below 4 microns) are therefore suspect.

Large scale decreases in the microscale, however, are matched at nearly every location by a jump in the velocity fluctuation, in both the streamwise and normal components. The microscale (a frequency-derived parameter) is therefore inversely related to velocity fluctuation (a direct measurement parameter). Trends in the microscale behavior are therefore significant, even if the microscale magnitude is suspect. The same is true of the trends in the energy dissipation rate, for the same reason.

The turbulence decay through the passage is actually a decay/excitation process. The excitation mechanism appears to strongly influence the microscale early in the passage, with little or no increase in turbulence intensity. Both the turbulence intensity and the integral scale appear to be immune to the significant changes in the microscale.

Turbulent kinetic energy dissipation rate and normal velocity component fluctuation are essential tools in decoding the complex relationships in the passage. The center passage turbulence appears to be influenced first by turbulent events near the suction surface, then by events near the pressure surface. This influence is apparently effected by sudden increases in v', which enables diffusion of turbulent kinetic energy in the normal direction. The dominant turbulent energy dissipation for all points in the passage occurs in the streamwise component.

VII. Recommendations

This investigation into the influence of the local turbulence parameters on convective heat transfer can be easily continued once the inlet velocity profile is under control. It appears that this control can be achieved with some mechanical improvements to the test section.

The behavior of the turbulence intensity and the two scale parameters in the passage invites further study, but it will be necessary to isolate the effects of turning, acceleration, and increased vortex activity before the excitation mechanism can be identified. A simple experiment in which the flow neither accelerates nor turns, but acquires a small vortex in one portion of the flow, will enable the decay/excitation process to be analyzed in a fully controlled environment. Similar experiments in which the flow experiences a strong pressure gradient (streamwise only; then normal to streamline) are also essential. The relationship between the three parameters and these influences must be identified before further attempts to analyze their behavior in the complex flow field of the turbine passage. Analysis of v' levels and energy dissipation rates in both components is strongly recommended.

7.1 Wind tunnel

Some modification to the wind tunnel test section will be necessary to continue this investigation. The following modifications are listed in order of importance.

1. Construct continuously variable inlet sideboards that can be manually controlled from outside the tunnel while the tunnel is

running. Three degrees of freedom for each board will be required: translation in two axes plus rotation about the Z axis. Three jackscrew mechanisms per board are therefore required. It may be necessary to move the bellmouth section farther upstream to allow sufficient room for this device for sideboard 1.

2 Install a total pressure tube array upstream of the cascade inlet, with at least ten tubes of small diameter. These can be connected to a manometer bank, so that the operator can immediately see the inlet velocity profile, and adjust the inlet sideboards to obtain a uniform velocity distribution ahead of the instrumented blade(s). It will probably prove necessary to make the grid tube mount adjustable also, so that the tube spacing and/or position (constant X, variable Y coordinate) are available to obtain the desired velocity profile as the secondary flow increases.

3 Instrument Blade 3 for surface pressure, with tap locations identical to Blade 2. This will enable the pressure coefficient profiles for the two blades to be compared as a crosscheck on the inlet velocity profiles.

4 Instrument Blade 3 for heat transfer in the same manner as Blade 2.

5 Modify Blades 1 and 4 to hold boundary layer hot wire probes. The mounts should be horizontal, to enable boundary layer

turbulence measurement on the pressure surface of Blade 2 and the suction surface of Blade 3. Fine control of horizontal distance while the tunnel is running is essential.

6 Install faster pressure sampling transducer with at least 4 psi range. If this cannot be done, change the Scanivalve sampling order to measure the pitot-static tube before, during and after the blade surface taps are sampled. Install a Scanivalve transducer module with greater pressure range: the tunnel had to be throttled down during this study to prevent suction surface pressures from exceeding the transducer range.

7 Provide a linen screen at the tunnel bellmouth to filter bugs out of the primary flow.

7.2 Turbulence generation device

1 Reduce the jet orifice diameter, or provide an additional source of secondary flow; the large compressor and the shop air are insufficient for stable plenum pressures above 30 psi with ten tubes in the grid. A large cyclone separator should be built to remove the copious amounts of entrained water and oil. The secondary plenum traps much of the liquids, but some is still injected into the primary flow - a hazard for the hot wire probe work.

2 In addition to making the tube spacing variable, single direction tubes should be used as integral parts of the sideboards, to reduce the high-speed flow near the sideboard as the secondary flow increases.

7.3 Turbulence measurement support

1 The Zenith PC needs a larger capacity hard drive. In one hour of test time the data acquisition system is capable of filling the current 20 MB drive with turbulence data alone.

2 A more efficient data reduction path should be developed to reduce the time required. Mainframe programs exist which can be modified for this purpose.

3 Install a miniature microphone system on a hot wire probe to enable simultaneous measurement of pressure fluctuations near the velocity measurement point.

7.4 Turbulence modelling

1 Fractals and Fractional Calculus

The nature of turbulence and of turbulence decay suggests that some of the characteristics of the flow might be predicted more accurately with a mathematic model that combines uniform flow terms with fractal function terms. Fractal functions are related to fractional derivatives (Bagley, 1990); Tatom describes an application of fractional calculus to stochastic spectra analysis (simulation of turbulent gusts) (Tatom 1990).

2 Frequency distribution analysis

The data path (Figure D.1) is fairly robust for homogeneous and isotropic turbulence flow. The scheme showed definite weakness in some flow regimes where the flow behavior departed significantly from the uniform flow model. In these regimes, the conversion of effective velocities to flow speed (U_{inf}) and angle (β) was the point of breakdown. Unfortunately it is these same regimes which are of major interest: regimes in which homogeneous turbulence is not fully developed; rather, the eddies have structure. This structured turbulence is strong enough to exceed the geometric limits of the flow model by which the probe was calibrated. This precludes the conversion of voltage data to velocity data.

A modification to the data path may improve the data reduction robustness, by incorporating a frequency distribution fit. The voltages recorded may be fed directly into the FFT algorithm, and the resulting frequency distribution can then be analyzed. The turbulence scales can be generated from the velocity frequency distribution directly.

The recorded voltages can also be distributed into a sequence of "bins", so that the population in a bin represents the relative frequency with which voltages appear in a particular voltage range (Wiesel, 1990). The frequency distribution is therefore a probability distribution ($f(E)$) and can be modelled

(e.g., with a Weibull or a lognormal distribution). The parameters of the distribution function would then be functions of flow geometry, and could be extracted from the calibration process. The "method of transformations" allows this voltage distribution to be transformed into a velocity distribution ($g(u)$) for each wire:

$$f(E) = g(u)\left|\frac{du}{dE}\right|$$

The velocity fluctuation information can then be withdrawn from the velocity distributions (in terms of variance) for computing Reynolds stresses and turbulent energy dissipation.

Thus the inherent weakness in the flow geometry (post wakes, beta values exceeding calibration limits, etc.) may be avoided, yet still produce useful flow parameters, since the effects of these difficult features are preserved in the frequency distribution and in the velocity probability distribution. This would also allow removal of background noise due to the probe itself, or to the base level of turbulence in the tunnel, so that the effect of the turbulence generator on the free stream turbulence might be better isolated.

References

Bagley, 1990. Bagley, Lt Col R. L., Professor of Mechanics. Personal interview. AFIT/ENY, Wright-Patterson AFB, OH. 19 October 1990.

Blair et al., 1983a. Blair, M. F., et al. "Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer and Mean Profile Development: Part II - Analysis of Results," *Journal of Turbomachinery, 111*: 97-103 (January 1989b)

Bradshaw, 1971. Bradshaw, P.; *An Introduction to Turbulence and its Measurement*. New York: Pergamon Press, 1971.

Cebeci and Smith, 1974. Cebeci, T., and A. O. Smith; *Analysis of Turbulent Boundary Layers*. New York: Academic Press, 1974.

Galassi, 1989. Galassi, Capt Lello. *Turbulence Scale Effects on Heat Transfer in a Linear Turbine Cascade*. MSAE thesis, AFIT/GAE/ENY/89D-11. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, December 1989.

Hinze, 1959. Hinze, J. O.; *Turbulence: An Introduction to its Mechanism and Theory*. New York: McGraw-Hill, 1959.

Kays and Crawford, 1987. Kays, W. M., and M. E. Crawford; *Convective Heat and Mass Transfer*, 2nd ed. New York: McGraw-Hill, 1987.

King, 1990. King, Lt Col Paul I., Assistant Professor of Aerospace Engineering. Personal interviews. AFIT/ENY, Wright-Patterson AFB, OH. December 1989 through November 1990.

MacMullin et al., 1989. MacMullin, R. et al.; "Free-Stream Turbulence From a Circular Wall Jet on a Flat Plate Heat Transfer and Boundary Layer Flow," *Journal of Turbomachinery, 111*: 78-86 (January 1989).

Pollock, 1985. Pollock, D. D.; *Electrical Conduction in Solids: An Introduction*, American Society for Metals, 1985.

Priddy and Bayley, 1985. Priddy, W. J. and F. J. Bayley. "Effects of Free Stream Turbulence on the Distribution of Heat Transfer Around Turbine Blade Sections," *International Journal of Heat and Fluid Flow, 6 (#3)*: 181-192 (September 1985).

Priddy and Bayley, 1988. Priddy, W. J. and F. J. Bayley. "Turbulence Measurement in Turbine Blade Passages and Implications for Heat Transfer," *Journal of Turbomachinery, 110*: 73-79 (January 1988).

Tatom, 1990. Tatom, F. B. *The Application of Fractional Calculus to Noise Simulation: Final Report*, June 1990. Contract NAS8-38452. Marshall Space Flight Center; Engineering Analysis, Inc, Huntsville AL.

Weisel, 1990. Weisel, W. E. Jr., Professor of Astronautical Engineering. Personal interview. AFIT/ENY, Wright-Patterson AFB, OH. 19 October 1990.

Appendix

A. *Blade Construction Details*

1 Blade Profile

The blade profile is taken from manually digitized data from the profile provided by Moore, who had constructed a replica of the Langston blade (Langston et al., 1977).

X, inches	Y, inches
-2.290000E-003	2.013180E-001
-1.258200E-002	2.516484E-001
-3.523100E-002	3.019800E-001
-6.291200E-002	3.523077E-001
-9.562600E-002	4.026370E-001
-1.258240E-001	4.529671E-001
-1.597970E-001	5.032968E-001
-2.340330E-001	5.952580E-001
-3.309180E-001	7.046155E-001
-4.479340E-001	8.052748E-001
-5.913760E-001	9.059345E-001
-7.838850E-001	1.00659
-1.04811	1.0846
-1.21798	1.10851
-1.3891	1.09719
-1.51996	1.06951
-1.70114	1.00659
-1.88988	9.059345E-001
-2.03835	8.052748E-001
-2.15914	7.046155E-001
-2.2598	6.039562E-001
-2.3504	5.032968E-001
-2.43092	4.051540E-001
-2.51648	2.967534E-001
-2.58695	2.013187E-001
-2.65489	1.006594E-001
-2.72535	-2.516484E-003
-2.78826	-9.814285E-002
-2.84866	-2.050934E-001
-2.90402	-3.019780E-001

-2.96442	-4.026370E-001	
-3.01852	-5.032968E-001	
-3.07011	-6.039562E-001	
-3.12044	-6.972660E-001	
-3.17454	-8.052748E-001	
-3.22487	-9.059345E-001	
-3.27269	-1.00659	
-3.32176	-1.10725	
-3.37284	-1.21008	
-3.4199	-1.30857	
-3.46268	-1.40249	
-3.51301	-1.50989	
-3.5558	-1.607[illegible]3	
-3.60235	-1.71121	
-3.64387	-1.80087	
-3.68917	-1.91253	
-3.73069	-2.01319	
-3.7395	-2.06352	
-3.72817	-2.11385	
-3.68665	-2.15663	trailing edge
-3.63884	-2.16971	Tap 11
-3.56838	-2.15663	
-3.4954	-2.06603	
-3.44003	-1.96933	
-3.37712	-1.86471	
-3.31924	-1.76154	
-3.2664	-1.6715	
-3.19971	-1.56022	
-3.14309	-1.46334	
-3.08269	-1.36557	
-3.01726	-1.26076	
-2.94806	-1.1601	
-2.88138	-1.05944	
-2.80588	-9.524888E-001	
-2.74045	-8.621625E-001	
-2.66496	-7.625588E-001	
-2.57688	-6.542858E-001	
-2.49132	-5.536265E-001	
-2.40073	-4.504506E-001	
-2.31013	-3.598471E-001	
-2.19941	-2.552757E-001	
-2.07484	-1.497138E-001	
-1.94147	-4.781319E-002	
-1.78041	5.032968E-002	
-1.56525	1.509890E-001	
-1.42433	2.013187E-001	
-1.25321	2.390660E-001	
-1.06196	2.503902E-001	
-8.845400E-001	2.340330E-001	

-7.197100E-001	2.050934E-001
-5.284600E-001	1.459561E-001
-3.321800E-001	4.529671E-002
-2.654900E-001	1.006594E-002
-1.988000E-001	0.000000E+000
-1.258200E-001	2.139011E-002
-7.549000E-002	5.410441E-002
-2.894000E-002	1.056923E-001
-2.516500E-003	1.761539E-001
-2.289900E-003	2.013187E-001

2 Instrumented Blade Construction

Initially, the Turbine Cascade Test Facility was equipped with four aluminum blades, two of which were tapped for surface pressures. A mold was built from one of the pressure tapped blades. This mold was used to fabricate blades 2 and 3 out of urethane foam. Blade #2 was cut in half to allow pressure tap tubing and thermocouples to be mounted in the interior.

The heated foil was stainless steel shim stock (0.002 in. nominal thickness), Stock number 22L-2, made by Precision Brand out of cold-rolled type 302 (Austenitic) stainless steel. The dimensions of the foil strip were 2.00 in. X 10.38 in. Copper bus bars were silver soldered to the foil ends, so that the contact area was 0.60 in. X 0.25 in. The rectangular contact area was located at the lower aft corner of the ends of the foil, as the bus bars continued down through the bottom surface of the blade and out of the test section. Only the foil appeared on the blade surface, and the foil was smooth and free of irregularities, so that it matched the blade profile.

Each of the 23 surface thermocouples were silver soldered (Sn 63) to the foil underside prior to attaching the foil to the blade

halves. Electrical grounding between thermocouples was prevented by the urethane foam. The five internal thermocouples were attached to the inside of the blade halves with silver-based epoxy. All 28 thermocouples were mounted in the plane of the centerline of the foil strip. The foil began on the pressure side 0.25 in. from the trailing edge, wrapped around the leading edge, and continued to 0.25 in. from the trailing edge on the suction side. Thermocouple #11, on the extreme trailing edge, was not under any foil, but was covered only by a thin coat of white paint. Thermocouple #10 was not located chordwise where its corresponding pressure tap was: the tap location occurred at the extreme edge of the foil, so thermocouple 10 was moved slightly toward the leading edge of the blade so as to fit under the foil.

B. Foil Resistivity Experiment

The heat generation rate in the foil is a crucial part of this study. The material property of resistivity is derived from the measurable properties of resistance and geometry. It is defined as

$$\rho = \frac{A_{cs} R}{L}$$

where A_{cs} is the cross section area normal to the current flow

R is the measured resistance (ohms)

L is the distance parallel to the current flow

For the heat flux computation, the desired quantity is R", or the resistance per unit surface area. This appears in the energy balance equation for a portion of the heated foil:

$$Q_{generated} = Q_{conducted away} + Q_{radiated away} + Q_{convected away}$$

This expands to

$$I^2 R'' w dl = k_{foam}(T_i - T_j) w dl dz + \sigma \epsilon_{foil}(T_i^4 - T_\infty^4) w dl + h(T_i - T_\infty) w dl$$

where I is the current flowing through the foil

w is the foil width

dl is the unit distance in the direction of the current

k_{foam} is the thermal conductivity of the urethane foam

T_i is the surface temperature at location i

T_j is the internal temperature of the foam

dz is the distance normal to the foil to the internal

temperature T_j

σ is the Stefan- Boltzmann constant

ϵ_{foil} is the emmissivity of the foil

h is the convection heat transfer coefficient

If t is the foil thickness, the value of R" is derived from

$$R'' = \frac{R}{wL} = \frac{\rho}{w^2 t}$$

For some metals, the resistivity is a strong function of temperature. The resistivity value of the foil (cold-rolled 302 stainless steel) was not available in materials handbooks. A simple experiment provided reasonably accurate information. A sample of the foil material was cut to the same width (2.00 in.), 6.6 in. long, and fitted with copper clamps at each end. The foil was then clamped between two plywood blocks, the upper block fitted with a copper wire (Figure B.1). A similar block clamped an identical wire 3.17 in. away. The temperature of the foil was measured by a thermocouple taped to the undersurface. Fiberglass batting insulated the foil above and below in the region between the blocks to hinder convective transients.

Current was applied to the foil via the copper clamps to generate heat and produce a voltage drop across the two copper wire contacts. The foil temperature was allowed to stabilize, and the temperature, voltage and current were recorded.

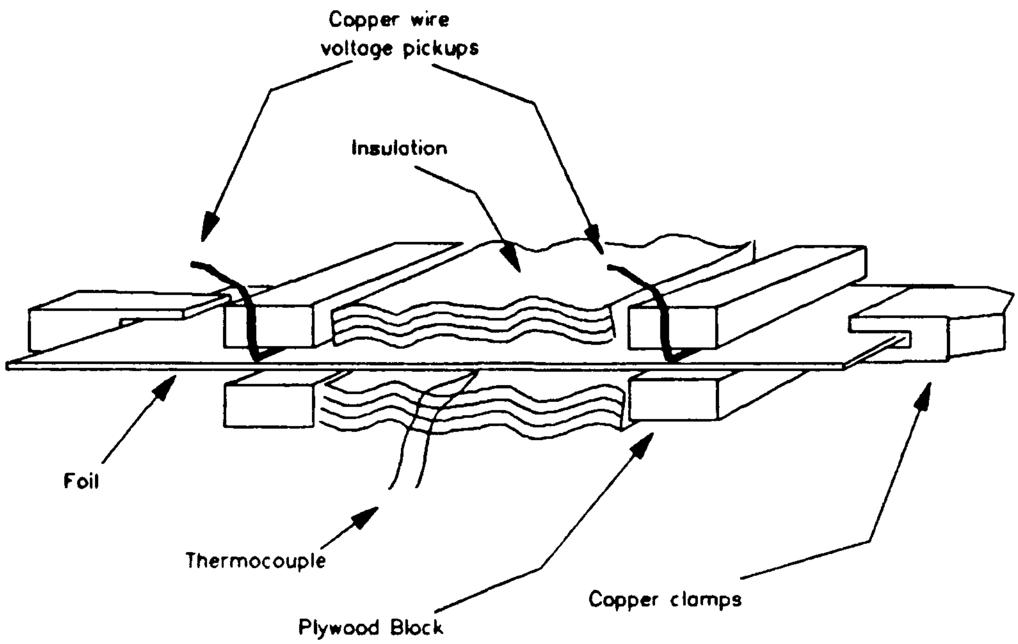


Figure B.1 Foil Resistivity Experiment

The results showed a mild temperature dependence:

$$\rho(\Omega - cm) = 3.48 \cdot 10^{-8} \cdot T + 8.27 \cdot 10^{-5}$$

where T is the temperature in degrees Fahrenheit. This gives a resistivity 18% higher than the handbook value for type 302 stainless steel at 68 F ($72\ \mu\Omega - cm$). The difference is attributed to the cold working of the foil sample, which is known to cause increases in resistivity [Pollock, 1985].

C. *Calibration*

1 *Hot Wire Calibration*

The original plan was to calibrate the hot-wire probes in the inlet section of the tunnel, using a flow constriction block to accelerate the flow to achieve the higher speeds to be encountered in the cascade passages. This approach did not work satisfactorily and was later abandoned. The first problems arose when the flow did not accelerate: total pressure losses were too high. A sheet aluminum fairing was installed behind the constriction block and wrapped around the #2 blade. The block and fairing could be installed or removed in a few minutes, by removing the #3 blade.

However, the fairing itself produced a second constriction in the exit plane, and the inlet calibration zone did not achieve the high velocity required. To alleviate this problem, #4 blade was removed and a second sheet metal fairing was installed to allow the flow to move around both sides of exit sideboard #3. This configuration produced the necessary velocity in the calibration zone.

It was then discovered that determination of the angle of the probe bisector angle was going to be difficult if not impossible, without exposing the fragile probe to contact with the plexiglas test sec-

tion roof. The probe mount was held by the index arms, and positioning the mount/index arms rig so that the mount tip protruded into the calibration section top was usually a rough maneuver. The probe was therefore inserted in the mount after the mount/index rig was installed in the calibration hole, so that the probe itself was nearly hidden from view. Direct, accurate measurement of the bisector angle of the installed probe was impossible in this configuration. This approach was abandoned in favor of the calibration tank.

2 *Hot Wire Calibration Source Code Listings*

a *XCAL3.BAS*

```
'             Hot wire (X type) calibration program
' Written by Lello Galassi  , 8/1/89.  Modified by Capt Acree 9/90
'
'    This calibration program reads the voltage output by each
wire
' during calibration testing.  Each channel is read 50 times, then
' averaged for a mean voltage.  The tank thermocouple is read and
stored
' automatically.  The manometer reading is input manually.
' Incompressible flow is assumed for velocity computation.
'    Ensure high speed cable is disconnected between the high
speed
' voltmeter and the dedicated FET module.  Attach tank Tcouple to
' Tcouple wire #29 (Channel 019 on the HP3852).
'   - Data is stored in 2 printable files in C:\lello\K###V_Tr.dat
'       where ### is probe #, V is either v or a, Tr is room temp(F)
'   - Data is stored in MCAD format (numbers only) in C:\MCAD\
'   - Permanent printable data stored in A:\CALIB\
'*****************************************************************
CLS
PRINT "***************************************************"
PRINT "X-wire calibration program for the HP 3852A"
PRINT "    HP44701 Integrating Voltmeter in slot 0600"
PRINT "---- High speed cable should be disconnected. ---"
PRINT "  Insert disk in Drive A for permanent storage in A:\CALIB
."
INPUT "File designator (last 3 Probe #s) to store data?  ", filena-
me$
INPUT "Current room temperature in deg F? ", tf$
```

```
INPUT "Corrected atmospheric pressure, in_Hg?  ", Patm
5  INPUT "Is this a (v)elocity or (a)ngle type calibration?  ",
var$
dir$ = "C:\LELLO\" + "K" + filename$ + var$ + "_" + tf$ + ".dat"
dirMcad$ = "C:\MCAD\" + "K" + filename$ + var$ + "_" + tf$ +
".dat"
dirstore$ = "A:\CALIB\K" + filename$ + var$ + "_" + tf$ + ".dat"
PRINT "    Printable data will be stored in "
PRINT dir$: PRINT dirstore$
PRINT "    MCAD data will be stored in ": PRINT dirMcad$
OPEN dir$ FOR OUTPUT AS #1: OPEN dirMcad$ FOR OUTPUT AS #2
OPEN dirstore$ FOR OUTPUT AS #3
PRINT #1, "    Calibration File for Probe#", filename$
PRINT #1, "      Date:", DATE$, TIMER / 3600
PRINT #3, "    Calibration File for Probe#", filename$
PRINT #3, "      Date:", DATE$, TIMER / 3600

IF (var$ <> "v") THEN GOTO 8
PRINT #1, "  Patm", "Room Temp", "Air Density"
PRINT #1, "  in_Hg", "  deg C", "  kg/m^3"
PRINT #3, "  Patm", "Room Temp", "Air Density"
PRINT #3, "  in_Hg", "  deg C", "  kg/m^3": GOTO 9

8 PRINT #1, "  Patm", "Tank Q", "Air Density"
  PRINT #1, "  in_Hg", "  m/sec", "  kg/m^3"
  PRINT #3, "  Patm", "Tank Q", "Air Density"
  PRINT #3, "  in_Hg", "  m/sec", "  kg/m^3"

9 PRINT "     Press any key to continue."
DO: LOOP WHILE INKEY$ = "": CLS
PRINT "************ Scanning temperatures ***************"
BEEP
VIEW PRINT 8 TO 22
CALL IBFIND("hp3852", dvm%)
CALL IBWRT(dvm%, "rst")
rd$ = SPACE$(16)
' ---------Sense tank recovery temperature and room temperature
CALL IBWRT(dvm%, "USE 600;RST 600;REAL TT,TR; AZERO ONCE")
CALL IBWRT(dvm%, "CONFMEAS TEMPJ, 019, INTO TT")
CALL IBWRT(dvm%, "CONFMEAS TEMPJ, 020, INTO TR")
CALL IBWRT(dvm%, "VREAD TT")
CALL IBWRT(dvm%, "disp on;disp TT")
CALL IBRD(dvm%, rd$)
TT = VAL(rd$)
CALL IBWRT(dvm%, "VREAD TR")
CALL IBWRT(dvm%, "DISP TR")
CALL IBRD(dvm%, rd$)
TR = VAL(rd$)
BEEP
PRINT "Current room temperature (F) is", (TR * 9! / 5!) + 32!
```

```
PRINT "Tank recovery temperature is", TT, "degC "
' -------------------------------- Compute current air density,
rho!
'rholow! = 1.3947: drho! = .4666: Tlow! = 23.15: dTemp! = 100!
'rho! = rholow! - drho! * (TT + Tlow!) / dTemp!

rho! = (Patm * 3386.4) / (287.074 * (TT + 273.15))'----- Ideal Gas
Law
PRINT "Current air density is "; rho!; SPC(1); "kg/m^3"
CALL IBWRT(dvm%, "rst 600")
IF (var$ <> "v") THEN
    INPUT "Current q? ", q!
    TR = SQR(q! * 248.7 * 2 / rho!)      'Good for 70 F
END IF
PRINT #1, Patm, TR, rho!
PRINT #1, "Vel/Ang", "Chan 1", "Chan 2", "Ttank", "Tstatic"
PRINT #3, Patm, TR, rho!
PRINT #3, "Vel/Ang", "Chan 1", "Chan 2", "Ttank", "Tstatic"

10  PRINT "Press any key to begin scan "
DO: LOOP WHILE INKEY$ = ""
PRINT "    Scanning tank temperature & voltages.": BEEP
' This call configures the HP44701 Integrating Voltmeter as the
measuring
' instument.
'-------------------------------------- Sense current tank recov-
ery temp.
CALL IBWRT(dvm%, "RST 600;REAL TTr; AZERO ONCE")
CALL IBWRT(dvm%, "CONFMEAS TEMPJ, 019, USE 600, INTO TTr")
CALL IBWRT(dvm%, "VREAD TTr")
CALL IBRD(dvm%, rd$)
TTr = VAL(rd$)
'----------------- Procede with channel 1 and channel 2 voltage
scan.
CALL IBWRT(dvm%, "clr"): SLEEP 1
CALL IBWRT(dvm%, "disp off")
CALL IBWRT(dvm%, "real A(49),B(49),L,H,AV,S")
CALL IBWRT(dvm%, "rst 600;nplc 1")
CALL IBWRT(dvm%, "conf dcv;nrdgs 50;azero once")
CALL IBWRT(dvm%, "meas dcv,321,use 600,into A")
CALL IBWRT(dvm%, "conf dcv;nrdgs 50;azero once")
CALL IBWRT(dvm%, "meas dcv,322,use 600,into B")
CALL IBWRT(dvm%, "disp on")
BEEP: PRINT "  Scan complete: record q.": BEEP
'-------------------------------------- Find average voltage val-
ues
CALL IBWRT(dvm%, "stat L,H,AV,S,A")
CALL IBWRT(dvm%, "vread AV")
CALL IBRD(dvm%, rd$)
chan1! = VAL(rd$)
```

```
'---------------- Output to the screen and to the data storage file
COLOR 1, 7
PRINT "channel 1 voltage is:", chanl!
CALL IBWRT(dvm%, "stat L,H,AV,S,B")
CALL IBWRT(dvm%, "vread AV")
CALL IBRD(dvm%, rd$)
chan2! = VAL(rd$)
CALL IBWRT(dvm%, "clr")
PRINT "channel 2 voltage is:", chan2!
PRINT "Tank recovery temp is: ", TTr
IF (var$ = "v") THEN
   INPUT "Input the current tank pressure in inches of water ",
vel!
ELSE
   INPUT "Input the current angle setting ", vel!
END IF
' -------------------------- Compute approximate velocity at ori-
fice
IF (var$ = "v") THEN
  vell! = SQR(vel! * 248.7 * 2! / rho!)
  PRINT "current air speed is: ", vell!, " m/sec"
ELSE
  PRINT "current angle setting is:", vel!, "degrees from bisector"
END IF
'----------- Compute static temp using laminar recovery factor (.8)
Cp = 1004.4     'J/kg*K
TS = TTr - (.8 * vell! ^ 2) / (2 * Cp)
PRINT "Static temp computed as: ", TS
' Output to data storage file on disk C:
PRINT #1, vel!, chanl!, chan2!, TTr, TS:
PRINT #2, vel!, chanl!, chan2!, TTr, TS
PRINT #3, vel!, chanl!, chan2!, TTr, TS
INPUT "quit?  (y or n) ", q$
IF q$ <> "y" THEN
  GOTO 10
ELSE
  CLOSE #1: CLOSE #2: CLOSE #3
  PRINT "This stage of calibration completed - data stored in"
  PRINT dir$, dirMcad$, dirstore$
END IF
INPUT "Do an angle calibration for the current hot wire? (Y) or
(N)", rst$
IF (rst$ = "y") THEN
  CLS
  GOTO 5
END IF
END
```

b PROBECAL.MCD

Probecal.MCD program (MathCAD worksheet)

Calibration of the TSI 1240-TI.5 hot wire. Serial #: 8930
Voltmeter - HP 44701A Integrating voltmeter Date: 20 Sep 90

Units: $m \equiv 1L$ $kg \equiv 1M$ $sec \equiv 1T$ $degC \equiv 1Q$

$mps \equiv m\ sec^{-1}$ $g \equiv 9.807\ m\ sec^{-2}$ $N \equiv kg\ m\ sec^{-2}$

$Pa \equiv N\ m^{-2}$ $kPa \equiv 1000\ Pa$ $J \equiv N\ m$ $deg := \dfrac{\pi}{180}$

$in\_W \equiv .2485\ kPa$ $in\_Hg \equiv 3386.4\ Pa$

Environmental Conditions:

$T_o := 21.85$

$P_o := 29.261\ in\_Hg$

$P_o = \ \ Pa$

The TSi calibration tank was used to calibrate all hot wire measurements. The incompressible Bernoulli Equation is used to convert all pressure readings to velocity.

$R \equiv 287.074\ J\ kg^{-1}\ degC^{-1}$

$$\rho := \frac{P_o}{R\left[T_o + 273.15\right] degC} \qquad \rho = \ \ kg\ m^{-3}$$

Angle calibration manometer reading: $dh1 \equiv 15.01\ in\_W$

Data files are stored on 3.5" disk titled CALIBRATION. ???

DeWitt,"Intro. to Heat Transfer", Table A.4, page 681.

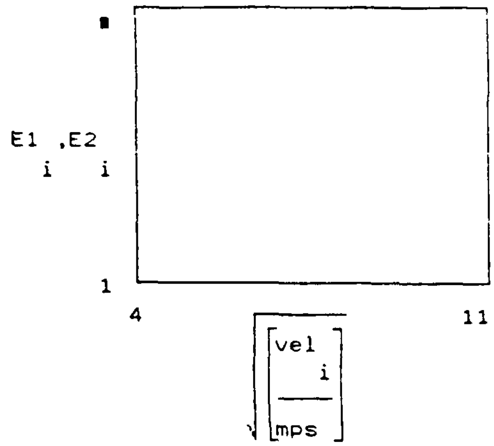
Read in the data for the x-wire calibration:

$dh := READPRN(K930v\_70\ dat)$ $vel := dh^{\langle 0 \rangle}\ mps$ $E1 := dh^{\langle 1 \rangle}$

$angcal := READPRN(K930a\_70\ dat)$ $E2 := dh^{\langle 2 \rangle}$

$n := length(vel)$ $i := 0\ ..n - 1$

Signal vs sqr root of velocity:



GoTo 305 for final tweaking.

uncertainty in air flow velocity

$$velerr := \sqrt{\left[\frac{2}{\rho}\right] .025\ in\_W}$$

velerr = mps

Raw data tabulation:

$vel_i\ mps^{-1} =$ $E1_i =$ $E2_i =$

Determine the constants of the calibration equation:

Channel 1

$$U1_{eff} := \left[\frac{vel}{mps}\left[(\cos(45\ deg))^2 + k1\ (\sin(45\ deg))^2\right]^{\frac{1}{2}}\right]^{\frac{1}{2}}$$

Channel 2

$$U2_{eff} := \left[\frac{vel}{mps}\left[(\cos(45\ deg))^2 + k2\ (\sin(45\ deg))^2\right]^{\frac{1}{2}}\right]^{\frac{1}{2}}$$

$$U12_{eff} := \overrightarrow{\left[\left[U1_{eff}\right]^2\right]} \qquad U22_{eff} := \overrightarrow{\left[\left[U2_{eff}\right]^2\right]}$$

Construct W matrices:

$$W1_{i,0} := 1 \qquad W2_{i,0} := 1$$

$$W1^{\langle 1\rangle} := U1_{eff} \qquad W1^{\langle 2\rangle} := U12_{eff}$$

$$W2^{\langle 1\rangle} := U2_{eff} \qquad W2^{\langle 2\rangle} := U22_{eff}$$

$$ESQ1 := \overrightarrow{\left[E1^2\right]} \qquad ESQ2 := \overrightarrow{\left[E2^2\right]}$$

$$b := \left(W1^T \cdot W1\right)^{-1} \cdot \left(W1^T\ ESQ1\right) \qquad b1 := \left(W2^T \cdot W2\right)^{-1} \left(W2^T\ ESQ2\right)$$

$b =$ $\qquad$ $b1 =$

$$quad1\left[U1_{eff}\right] := b_0 + b_1\left[U1_{eff}\right] + b_2\ U1_{eff}^{\ 2}$$

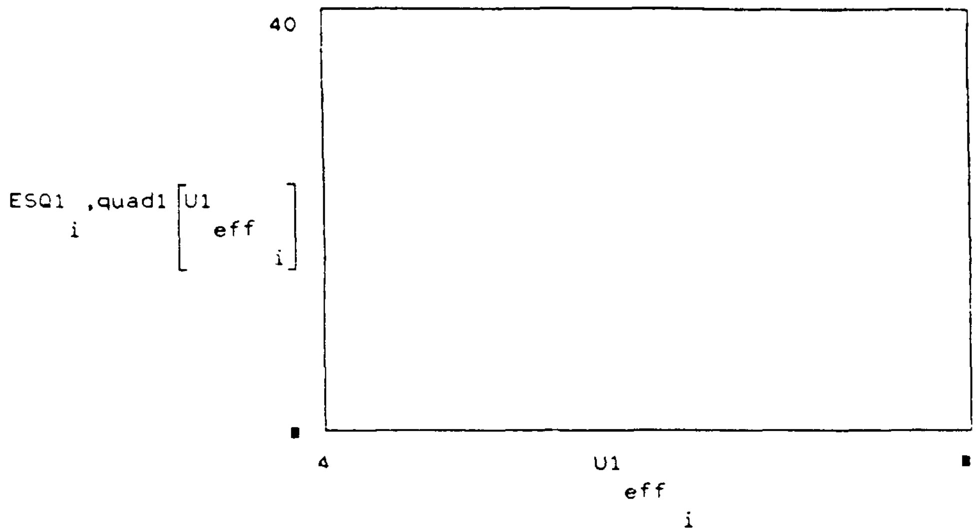
$$quad2\left[U2_{eff}\right] := b1_0 + b1_1\left[U2_{eff}\right] + b1_2\ U2_{eff}^{\ 2}$$

$$SSE1_Q := \Sigma\overrightarrow{\left[\left[ESQ1 - quad1\left[U1_{eff}\right]\right]\right]^2} \qquad SSE2_Q := \Sigma\overrightarrow{\left[\left[ESQ2 - quad2\left[U2_{eff}\right]\right]\right]^2}$$

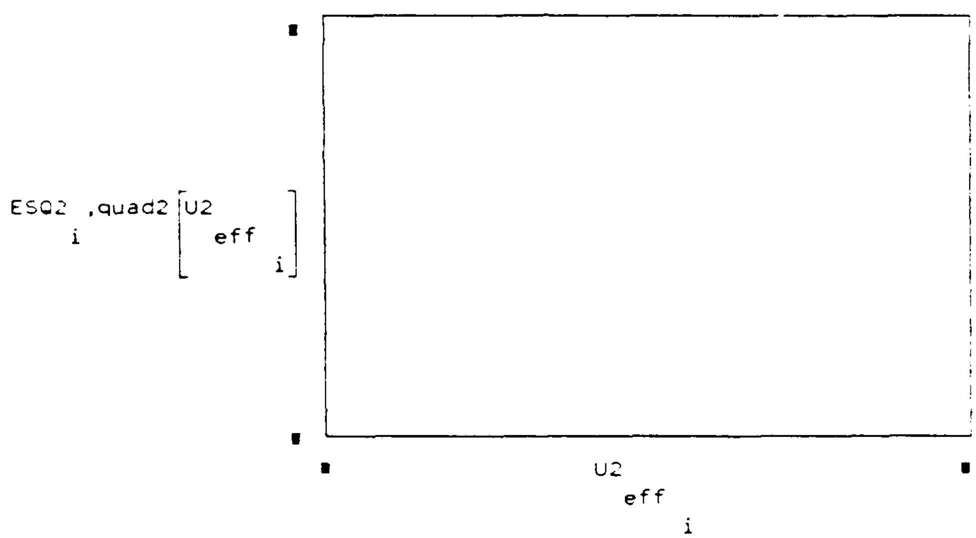
$$MSE1_Q := \frac{SSE1_Q}{n - 2} \qquad MSE2_Q := \frac{SSE2_Q}{n - 2}$$

$MSE1_Q =$ $\qquad$ $MSE2_Q =$

Channel 1 Calibration Curve



Channel 2 Calibration Curve



Read the angle calibration data into vectors:

$dh1 = \quad in\_W$

$\theta := angcal^{\langle 0 \rangle}$ $\quad e1 := angcal^{\langle 1 \rangle}$

$e2 := angcal^{\langle 2 \rangle}$

$$U_i := \left[\sqrt{\left[\frac{2}{\rho}\right] dh1}\right]$$

$$U_i = \quad m\ sec^{-1}$$

$$U1_{eff} := \left[\frac{U_{\Phi}}{mps}\right]^{\frac{1}{2}} \cdot \overrightarrow{\left[\left[(\cos((45-\theta)\,deg))^{2} + k1\,(\sin((45-\theta)\,deg))^{2}\right]^{\frac{1}{4}}\right]}$$

$$U2_{eff} := \left[\frac{U_{\Phi}}{mps}\right]^{\frac{1}{2}} \cdot \overrightarrow{\left[\left[(\cos((45+\theta)\,deg))^{2} + k2\cdot(\sin((45+\theta)\,deg))^{2}\right]^{\frac{1}{4}}\right]}$$

$$E1theory := \overrightarrow{\left[\left[b_{0} + b_{1}\cdot U1_{eff} + b_{2}\cdot U1_{eff}\right]^{2}\right]^{\frac{1}{2}}}$$

$$E2theory := \overrightarrow{\left[\left[b1_{0} + b1_{1}\, U2_{eff} + b1_{2}\cdot U2_{eff}\right]^{2}\right]^{\frac{1}{2}}}$$

$$err1 := \overrightarrow{\left[(E1theory - e1)^{2}\right]} \qquad err2 := \overrightarrow{\left[(E2theory - e2)^{2}\right]}$$

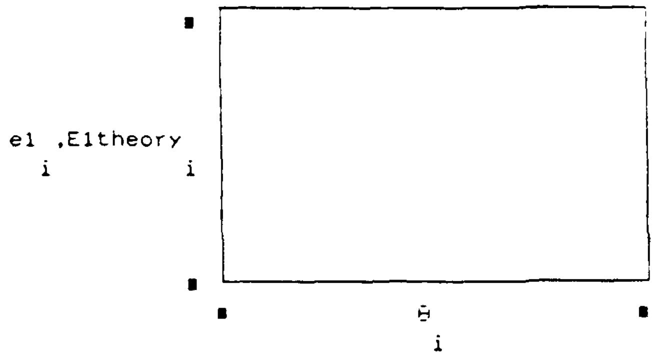
$m := last(\theta)$ $\quad m =$ $\quad i := 0\,..m$

Minimum squared error:

$errsum1 := \Sigma err1$ $\qquad errsum1 =$

$errsum2 := \Sigma err2$ $\qquad errsum2 =$

$\theta_i =$ $\quad e1_i =$ $\quad E1theory_i$ $\quad err1_i =$ $\quad e2_i =$ $\quad E2theory_i$ $\quad err2_i =$

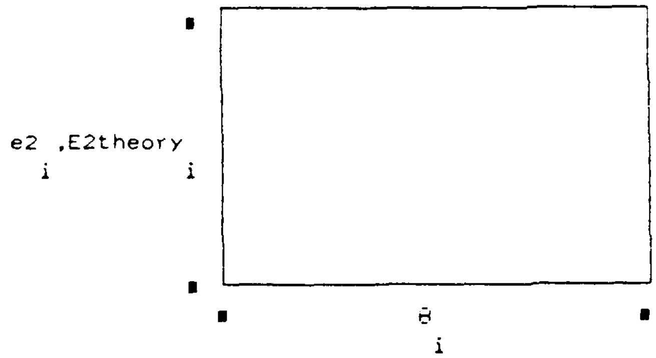


Proper selection of k1 and k2 minimize the sum of the squared error.

k1 ≡ .121

errsum1 =

k2 ≡ .119



errsum2 =

Calibration TSI 1240 - Ti.5 SR# 8930 (date: 20 Sep 90, Acree)
The coefficients for each equation is given as follows:

b =

k1 =

b1 =

k2 =

3 Hot Wire Calibration Procedure

Prior to performing the calibration procedure, the angle between the tungsten wires should be measured under a microscope. This is easily done with an average microscope equipped with lateral stage motion. An American Optical Series 10 monocular microscope was used to measure the angles of the probes. This instrument was equipped with lateral stage motion, and a spring-loaded slide holder that provided the right amount of gripping force on the probe body.

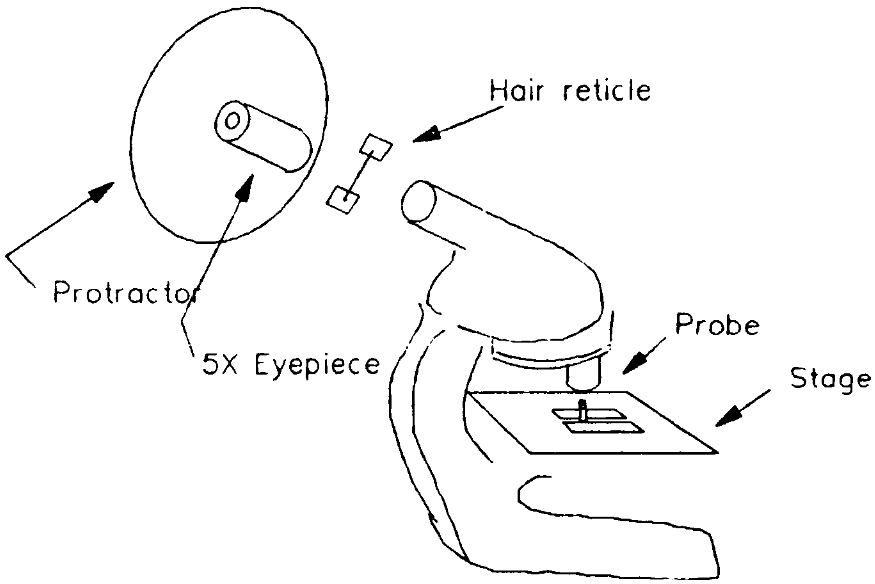


Figure C.1 Microscope Reticle Placement

Figure C.1 shows the protractor and human hair reticle arrangement employed. It is important to place the hair across the field of vision as close as possible to the point where the image converges to a point; this makes the hair appear nearly in focus and superimposed

on the image of the probe wires. The lens diagram in the microscope manual identified this spot as being near the bottom lens of the removable eyepiece, where it was not difficult to tape the hair across the field of view.

The orientation of the probe under the microscope must be carefully identified and repeated for each probe. Figure C.2 shows the orientation that worked well: the extra glass slides help hold the probe near the center of the stage lateral motion range. The hair reticle is rotated to align with a particular wire by turning the protractor attached to the eyepiece.

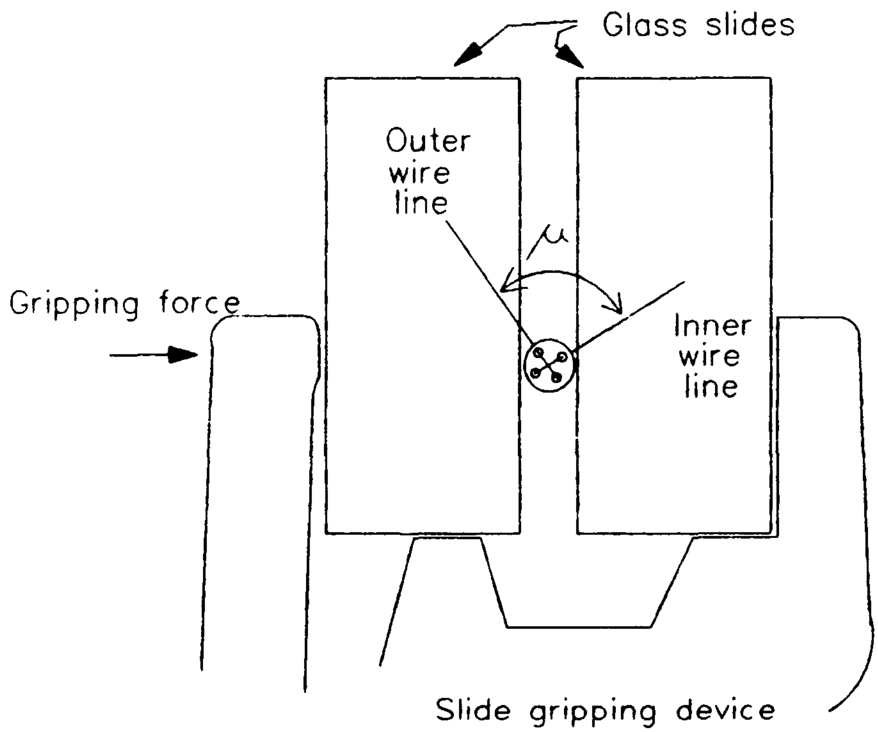


Figure C.2 Probe Mounting Detail

The following procedure ensures that the calibration flow streamlines impinge on the probe wires along the bisector of the angle μ.

X-wire Calibration Procedure

1. Read the local atmospheric pressure: correct for temperature and latitude. Load XCAL3.BAS after loading QuickBASIC with the GPIB libraries (See batch file GO.BAT in C: for rapid start).

2. Check the high speed voltmeter module in the HP 3852A: the ribbon cable from the adjacent FET module should be disconnected. Turn on the HP 3852A and let it warm up for an hour to ensure accurate temperature measurements. Turn on the IFA-100 and the oscilloscope. Connect the two cables to the appropriate mount (labelled "A") couplings. Connect the tank thermocouple (type J) lead to wire #29, and room thermocouple to #30. These correspond to channels 019 and 020 in the FET module.

3. Install a probe in the probe mount by lining up the black mark on the probe body with the black mark on the mount tube end. Adjust the mount tube protector laterally, and the tank height adjustment, to place the probe wires directly in the center of the jet. Ensure that the probe tip is about 3-4 mm from the orifice.

4. Align the short support posts with the vertical using a magnifying glass. Loosen the angle pointer clamp, and move the pointer to indicate the $\mu/2$ angle for this probe (Fig. C.3), using ccw motion from the 0/180 degree mark. The pointer now is parallel to the probe

bisector. Tighten the pointer clamp, then rotate the pointer cw to the 0/180 index mark to align the bisector with the streamline exiting the tank orifice.

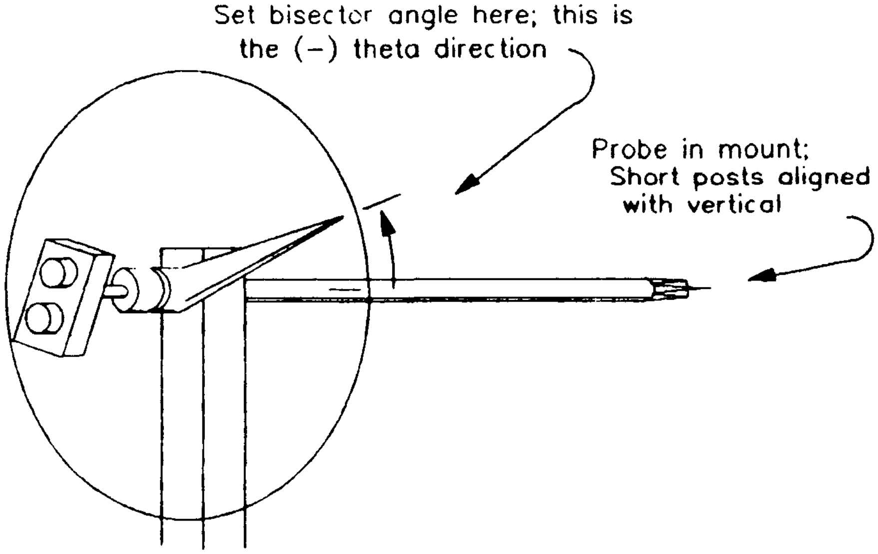


Figure C.3 Calibration Angle Adjustment Detail

5. Close the air valve on the TSi Model 1125 calibration tank. Hook up the long high pressure hose to the tank valve, with the other end connected to the jet grid manifold. Turn on the shop air valve connected to the cyclone dryer/filter unit. Connect the tank pressure line to the left fitting on the micromanometer, leaving the right fitting open to the atmosphere.

6. Set the IFA-100 controls for both channels:

Cable Res	Values from shorting procedure
Bridge Comp	35

Operate Res	Per probe box label
Cable Frequency Comp	Per IFA-100 manual
Gain	10
Filter	100000 Hz
Offset	1 volt
Output Display	Signal Conditioner

7. Open the valve to get about 3 in_W tank pressure. Set both channels to RUN on the IFA-100. Start the XCAL3 program. Make about 12-20 observations, increasing tank pressure by an appropriate increment to maximum expected velocity, then decreasing by a different decrement. Check for oscillation on both channels before taking a reading; adjust the cable freq. comp. a quarter turn ccw until the OSC light goes out.

8. The voltages should be between 2 and 6 volts. Confirm the screen displays with the IFA-100 Data display at each reading. Print the file when the velocity run is complete.

9. For the angle calibration set the tank pressure to the median value. Set the angle pointer to indicate 20 degrees ccw from the 0/180 mark: this represents theta = -20 deg. Take readings as before, using an angle increment of 2 deg until reaching theta = +20. Print the file.

10. Set both channels to STANDBY, then turn off the tank air valve. Turn off the shop air supply valve.

11. Exit QuickBASIC and go to the MCAD directory. Run MCAD and load PROBEKAL.MCD. Change the probe serial number, date, atmospheric pressure, and angle run pressure value. Change the file names in the two READPRN statements. Check each page for error messages, then adjust the k1 and k2 values to minimize the errsum values. Save under the filename K####_TT, where #### is the probe serial number and TT is the room temp in degF. Print the document and store it for a permanent record.

4 *Scanivalve Calibration Source Code Listing (SCANCAL)*

```
'Voltage test for Scanivalve pressure transducer
'Written by Capt J. L. Acree, 7/90
'The calibration data appears as pressure (kPa) and voltage.
CLS
LOCATE 10, 1
COLOR 1, 7
DIM CAL(30) AS SINGLE

'Initialize the program.
PRINT "Check Scanivalve power switches and 10.00 V supply voltage."
INPUT "Directory used to store the data file? (a:\) ", dir$
IF dir$ = "" THEN
        dir$ = "A:\"
END IF

INPUT "Name of file used to store data? (calib) ", flname$
IF flname$ = "" THEN
        flname$ = "calib"
END IF

OPEN dir$ + flname$ + ".dat" FOR OUTPUT AS #1

CALL ibfind("HP3852", dvm%)                    'Find the HP3852A
address
CALL IBWRT(dvm%, "RST")
CALL IBWRT(dvm%, "RST 600")
CALL IBWRT(dvm%, "REAL C(50), L,H,M,S")
CALL IBWRT(dvm%, "USE 600; NPLC 16")        'Configure the HP44701
for
                                              ' 5.5 digits of accuracy.


CALL IBWRT(dvm%, "SUB VOLTAGE")               'Create the measure-
ment subroutine
CALL IBWRT(dvm%, "AZERO ONCE,USE 600")
CALL IBWRT(dvm%, "CONF DCV; NRDGS 50")
CALL IBWRT(dvm%, "MEAS DCV, 221, USE 600, INTO C")
CALL IBWRT(dvm%, "STAT L,H,M,S,C")
CALL IBWRT(dvm%, "DISP M")
CALL IBWRT(dvm%, "VREAD M")
CALL IBWRT(dvm%, "SUBEND")

I = 1
PRINT "<Press> any key to begin calibration of scanivalve trans-
ducer"
PRINT
DO: LOOP WHILE INKEY$ = ""
DO
        COLOR 0, 3
        CALL IBWRT(dvm%, "CALL VOLTAGE")
```

```
        rd$ = SPACE$(16)
        CALL IBRD(dvm%, rd$)
        vt! = VAL(rd$)
        PRINT "Voltage output is: ", vt!
        INPUT "Manometer height difference? ", dh!
        dh! = dh! * .249
        PRINT #1, dh!, vt!
        INPUT "Continue? (y or n) ", ans$

        IF ans$ = "n" THEN
                EXIT DO
        END IF

        PRINT : PRINT "<Press> any key to continue"
        DO: LOOP WHILE INKEY$ = ""
        CLS 2: I = I + 1
LOOP

END
```

D. Data Acquisition and Reduction

1 Source Code Listings

a Data Acquisition Main Driver: MAINDRV#.BAS

```
'*******************************************************************
**
' HP3852A Data Acquisition Program for High Turbulence Heat
Transfer
' (for use on the Cascade Pilot Turbine Tunnel, BLDG 19)
'
' Written by Lt Lello Galassi, 6/23/89   Modified by Capt Acree
7/90
'*******************************************************************
**

        ' QuickBASIC Declarations Rev. C.4

' Common GPIB status variables

  COMMON SHARED ibsta%, iberr%, ibcnt%

' GPIB Subroutine Declarations
  DECLARE SUB IBBNA (BD%, BDNAME$)
  DECLARE SUB IBCAC (BD%, v%)
  DECLARE SUB IBCLR (BD%)
  DECLARE SUB IBCMD (BD%, CMD$)
  DECLARE SUB IBCMDA (BD%, CMD$)
  DECLARE SUB IBDMA (BD%, v%)
  DECLARE SUB IBEOS (BD%, v%)
  DECLARE SUB IBEOT (BD%, v%)
  DECLARE SUB IBFIND (BDNAME$, BD%)
  DECLARE SUB IBGTS (BD%, v%)
  DECLARE SUB IBIST (BD%, v%)
  DECLARE SUB IBLOC (BD%)
  DECLARE SUB IBONL (BD%, v%)
  DECLARE SUB IBPAD (BD%, v%)
  DECLARE SUB IBPCT (BD%)
  DECLARE SUB IBPPC (BD%, v%)
  DECLARE SUB ibrd (BD%, rd$)
  DECLARE SUB IBRDA (BD%, rd$)
  DECLARE SUB IBRDF (BD%, FLNAME$)
  DECLARE SUB IBRDI (BD%, IARR%(), CNT%)
  DECLARE SUB IBRDIA (BD%, IARR%(), CNT%)
  DECLARE SUB IBRPP (BD%, PPR%)
  DECLARE SUB IBRSC (BD%, v%)
  DECLARE SUB IBRSP (BD%, SPR%)
  DECLARE SUB IBRSV (BD%, v%)
  DECLARE SUB IBSAD (BD%, v%)
  DECLARE SUB IBSIC (BD%)
```

```
DECLARE SUB IBSRE (BD%, v%)
DECLARE SUB IBSTOP (BD%)
DECLARE SUB IBTMO (BD%, v%)
DECLARE SUB IBTRAP (MASK%, MODE%)
DECLARE SUB IBTRG (BD%)
DECLARE SUB IBWAIT (BD%, MASK%)
DECLARE SUB IBWRT (BD%, WRT$)
DECLARE SUB IBWRTA (BD%, WRT$)
DECLARE SUB IBWRTF (BD%, FLNAME$)
DECLARE SUB IBWRTI (BD%, IARR%(), CNT%)
DECLARE SUB IBWRTIA (BD%, IARR%(), CNT%)

' GPIB Function Declarations

DECLARE FUNCTION ILBNA% (BD%, BDNAME$)
DECLARE FUNCTION ILCAC% (BD%, v%)
DECLARE FUNCTION ILCLR% (BD%)
DECLARE FUNCTION ILCMD% (BD%, CMD$, CNT%)
DECLARE FUNCTION ILCMDA% (BD%, CMD$, CNT%)
DECLARE FUNCTION ILDMA% (BD%, v%)
DECLARE FUNCTION ILEOS% (BD%, v%)
DECLARE FUNCTION ILEOT% (BD%, v%)
DECLARE FUNCTION ILFIND% (BDNAME$)
DECLARE FUNCTION ILGTS% (BD%, v%)
DECLARE FUNCTION ILIST% (BD%, v%)
DECLARE FUNCTION ILLOC% (BD%)
DECLARE FUNCTION ILONL% (BD%, v%)
DECLARE FUNCTION ILPAD% (BD%, v%)
DECLARE FUNCTION ILPCT% (BD%)
DECLARE FUNCTION ILPPC% (BD%, v%)
DECLARE FUNCTION ILRD% (BD%, rd$, CNT%)
DECLARE FUNCTION ILRDA% (BD%, rd$, CNT%)
DECLARE FUNCTION ILRDF% (BD%, FLNAME$)
DECLARE FUNCTION ILRDI% (BD%, IARR%(), CNT%)
DECLARE FUNCTION ILRDIA% (BD%, IARR%(), CNT%)
DECLARE FUNCTION ILRPP% (BD%, PPR%)
DECLARE FUNCTION ILRSC% (BD%, v%)
DECLARE FUNCTION ILRSP% (BD%, SPR%)
DECLARE FUNCTION ILRSV% (BD%, v%)
DECLARE FUNCTION ILSAD% (BD%, v%)
DECLARE FUNCTION ILSIC% (BD%)
DECLARE FUNCTION ILSRE% (BD%, v%)
DECLARE FUNCTION ILSTOP% (BD%)
DECLARE FUNCTION ILTMO% (BD%, v%)
DECLARE FUNCTION ILTRAP% (MASK%, MODE%)
DECLARE FUNCTION ILTRG% (BD%)
DECLARE FUNCTION ILWAIT% (BD%, MASK%)
DECLARE FUNCTION ILWRT% (BD%, WRT$, CNT%)
DECLARE FUNCTION ILWRTA% (BD%, WRT$, CNT%)
```

```
  DECLARE FUNCTION ILWRTF% (BD%, FLNAME$)
  DECLARE FUNCTION ILWRTI% (BD%, IARR%(), CNT%)
  DECLARE FUNCTION ILWRTIA% (BD%, IARR%(), CNT%)

  DECLARE SUB TMON (dvm%)
  DECLARE SUB GPIBERR ()
  DECLARE SUB PRUN (dvm%, rho!, dt$, File$, iflag%, T!, q!)
  DECLARE SUB FRUN (dvm%, File$, X, Y, Z, PsiL)
  DECLARE SUB TRUN (dvm%, T!, File$, rho!, q!)
  DECLARE SUB CONVERT (VALS!(), nn%)
  DECLARE SUB FFT ()
  DECLARE SUB locatn (File$, PL, Z, X, Y, PsiL)
  DECLARE SUB PLOTT (xdatl!(), ydatl!(), xmin!, xmax!, ymin!,
ymax!, xlab$, ylab$, pltlab$, ntot%)
  DECLARE SUB SECFLO (dvm%, sfa!, sfT!)
  DECLARE SUB Troom (dvm%, T!)
  DECLARE SUB vector (dvm%, X, Y, Z, PsiL, u, Psi)
'*************************************************************
'*   High turbulence turbine blade heat transfer program      *
'*                                                            *
'*                MAIN DRIVER   -    L. Galassi, 6/23/89      *
'*************************************************************
DIM chord(24) AS SINGLE  'chord locations are common
'**********************************************    Initialize the
screen
CLS : COLOR 3, 0: LOCATE 7, 12
PRINT "HP3852 Controller Program": PRINT
LOCATE 8, 12
PRINT "Lt L. Galassi  6/23/89    Modified by Capt J. L. Acree
7/90"
LOCATE 10, 12
PRINT "This program controls the HP3852 Data Acquisition System"
LOCATE 11, 12
PRINT "for high-turbulence heat transfer measurements."
PRINT ""
SLEEP 5
CLS : LOCATE 7, 7
        INPUT "Bypass turn-on sequence? ", ans$
            IF ans$ = "y" THEN
                GOTO 55
            END IF

PRINT : PRINT "Initialization of Program:": PRINT

10 INPUT "HP3852 on? (y or n)", ans$
    IF ans$ <> "y" THEN
        BEEP
```

```
        PRINT "TURN ON HP3852"
        GOTO 10
    END IF
20 INPUT "Blade and Scanivalve power supplies on? (y or n)", ans$
    IF ans$ <> "y" THEN
        BEEP
        PRINT "TURN ON BOTH POWER SUPPLIES"
        GOTO 20
    END IF
30 INPUT "Scanivalve on? (y or n)", ans$
    IF ans$ <> "y" THEN
        BEEP
        PRINT "TURN ON SCANIVALVE"
        GOTO 30
    END IF
40 INPUT "IFA 100 on and channels set? (y or n)", ans$
    IF ans$ <> "y" THEN
        BEEP
        PRINT "SET-UP THE IFA 100"
        GOTO 40
    END IF
'*****************************************************************
*****
'Read the blade chord locations for pressure ports and thermocou-
ples
55 OPEN "C:\LELLO\chord.dat" FOR INPUT AS #2   'blade chord
locations are
FOR J = 1 TO 23                               'stored into the data
file
INPUT #2, chord(J)                            'chord.dat in the A:
drive.
'PRINT "chord(", J, ")=", CHORD(J)
NEXT J
CLOSE #2
'*****************************************************************
*****
' Initial Test parameters:
CLS : LOCATE 7, 7
PRINT : PRINT "Data initialization:": PRINT
INPUT "Run Designation for all data files ? ", File$
iflag% = 0
dt$ = DATE$: time& = TIMER
'*****************************************************************
**
'Assign a unique identifier to the HP3852 for use with the GPIB
```

```
CALL IBFIND("HP3852", dvm%)
IF dvm% < 0 THEN CALL GPIBERR
CALL IBWRT(dvm%, "RST"): CALL Troom(dvm%, T!)    '****** Get
room temp
'***********      Air density computation
**************************
rholow! = 1.3947: drho! = .4666: Tlow! = 23.15: dTemp! = 100!
rho! = rholow! - drho! * (T! + Tlow!) / dTemp!
CLS : LOCATE 7, 7
PRINT "Current air temperature is "; T!; SPC(1); "Celsius"
PRINT "Current air density is "; rho!; SPC(1); "kg/m^3"
LOCATE 12, 7
PRINT " Press any key to continue..."
DO: LOOP WHILE INKEY$ = ""
CLS : LOCATE 7, 7
PRINT : PRINT "Data Initialization Complete."

'HP3852A Slot assignment:
'       44713A  24 Ch. FET Mplexr                    Slot 000
'       44728A   8 Ch. Relay Actuator                Slot 100
'       44713A  24 Ch. FET Mplexr                    Slot 200
'       44713A  24 Ch. FET Mplexr (Hi-speed mode)    Slot 300
'       44702B  High-speed Voltmeter                 Slot 400 & 500
'       44701A  Integrating Voltmeter                Slot 600
'
'HP 44713A FET channel assignment is as follows:
'       221,222                  Scanivalve input
'       201-216,007-022          Thermocouple input (1-32)
'       321                      Hot wire (channel 1)
'       322                      Hot wire (channel 2)
'
'HP44728A Relay Actuator channel assignment:
'
'Channel 100             Scanivalve Step Control
'Channel 101             Scanivalve Home Control
'Channel 104             HP Blade Power Supply Control
'Channel 102,3,5-9       Not Used
'*****************************************************************
*

'************************         Routine Branching for the MAIN
MENU
DO
    CLS : PRINT : PRINT "         MAIN MENU": PRINT
    PRINT STRING$(80, "_"): PRINT
    PRINT "01) Temperature Run"
    PRINT "02) Pressure Run"
    PRINT "03) Turbulence Frequency Run"
    PRINT "04) Temperature and Frequency Run"
    PRINT "05) Temp., Freq., and Press. Run"
```

```
    PRINT "06) Frequency and Pressure Run"
    PRINT "07) Fast Fourier Transform of Data"
    PRINT "08) Current Temperature of the blade (Station 10)"
    PRINT "09) Secondary Flow Manifold Pressure & Temperature"
    PRINT "10) Change File Designator"
    PRINT "11) EXIT"
    PRINT : PRINT "Type your selection (01-11):"
    chs$ = INPUT$(2)

' Use SELECT CASE to process response.
    SELECT CASE chs$
        CASE "01": CALL TRUN(dvm%, T!, File$, rho!, q!)
        CASE "02": CALL PRUN(dvm%, rho!, dt$, File$, iflag%, T!,
q!)
        CASE "03": CALL FRUN(dvm%, File$, X, Y, Z, PsiL)
        CASE "04": CALL TRUN(dvm%, T!, File$, rho!, q!)
                CALL FRUN(dvm%, File$, X, Y, Z, PsiL)
        CASE "05": CALL TRUN(dvm%, T!, File$, rho!, q!)
                CALL PRUN(dvm%, rho!, dt$, File$, iflag%, T!, q!)
                CALL FRUN(dvm%, File$, X, Y, Z, PsiL)
        CASE "06": CALL PRUN(dvm%, rho!, dt$, File$, iflag%, T!,
q!)
                CALL FRUN(dvm%, File$, X, Y, Z, PsiL)
        CASE "07": CALL FFT
        CASE "08": CALL TMON(dvm%)
        CASE "09": CALL SECFLO(dvm%, sfa!, sfT!)
        CASE "10": CLS : INPUT "New file designation:", File$:
        CASE "11": DO: CLS : PRINT "Blade power off?": SLEEP 1
                 LOOP WHILE INKEY$ = "": EXIT DO
        CASE ELSE
            BEEP
    END SELECT
    LOOP
    END

SUB CONVERT (VALS!(), nn%)
     DEFINT I-M
     DIM VALS!(2049)
     N = 2 * nn
     J = 1
     FOR i = 1 TO N STEP 2
    IF J <= i THEN GOTO 2200
    TEMPR = VALS(J)
    TEMPI = VALS(J + 1)
    VALS(J) = VALS(i)
    VALS(J + 1) = VALS(i + 1)
    VALS(i) = TEMPR
```

```
    VALS(i + 1) = TEMPI
2200    m = N / 2
2210    IF m >= 2 AND J > m THEN GOTO 2240
    J = J + m
    GOTO 2310
2240    J = J - m
    m = m / 2
    GOTO 2210
2310 NEXT i
     MMAX = 2
2330 IF N <= MMAX THEN GOTO 2700
     ISTEP = 2 * MMAX
     THETA# = 6.28318530717959# / ISIGN / MMAX
     WPR# = -2 * (SIN(THETA# / 2) ^ 2)
     WPI# = SIN(THETA#)
     WR# = 1#
     WI# = 0.000000000000000
     FOR m = 1 TO MMAX STEP 2
    FOR i = m TO N STEP ISTEP
        J = i + MMAX
        TEMPR = CSNG(WR#) * VALS(J) - CSNG(WI#) * VALS(J + 1)
        TEMPI = CSNG(WR#) * VALS(J + 1) + CSNG(WI#) * VALS(J)
        VALS(J) = VALS(i) - TEMPR
        VALS(J + 1) = VALS(i + 1) - TEMPI
        VALS(i) = VALS(i) + TEMPR
        VALS(i + 1) = VALS(i + 1) + TEMPI
    NEXT i
    WTEMP# = WR#
    WR# = WR# * WPR# - WI# * WPI# + WR#
    WI# = WI# * WPR# + WTEMP# * WPI# + WI#
     NEXT m
     MMAX = ISTEP
     GOTO 2330
2700 'ALL DATA IS NOW CONVERTED AND IS READY TO BE STORED
     IF ISIGN = -1 THEN RETURN
     FOR i = 1 TO nn * 2
    VALS(i) = VALS(i) / nn
     NEXT i

     END SUB

DEFSNG I-M
SUB DVMERROR STATIC
PRINT "DVM GPIB ERROR"
END SUB
```

```
SUB FFT
    'THIS ROUTINE TRANSFORMS DATA FROM THE TIME TO FRE-
QUENCY DOMAIN
    'OR BACK USING THE DANIELSON-LANCZOS FFT METHOD
    'THE DATA FORMAT REQUIRED FOR READING IS AS FOLLOWS:
    '  TOP LINE:
    '   NN       C        R        ISIGN
    'WHERE NN = # OF SAMPLED DATA POINTS < 1025
    '       C  = # OF CHANNELS READ
    '       R  = (1) IF REAL DATA, (2) IF COMPLEX DATA, (3) IF
MAGNITUDE DATA
    '    ISIGN= (+1) IF DATA IS IN TIME DOMAIN, (-1) IF DATA IS
IN FREQ DOMAIN
    '
    '  REMAINING DATA:
    '   TIME OR FREQ    CH1     CH2     .....'
    '
     '********************* FFT ROUTINE *********************
     '******************** MAIN PROGRAM ************************
     DIM VALS!(2049)
     DIM VALU!(2049, 6)
     DIM VALM!(1025, 6)
     'GET DATA
     PRINT "AVAIL DATA FILES:"
     FILES "\LELLO\*.FFT"
     INPUT "INPUT DATA FILE NAME W/O EXTENSION (.FFT): "; ND$
     OPEN "\LELLO\" + ND$ + ".FFT" FOR INPUT AS #1
     INPUT #1, nn, c, R, ISIGN
     S1$ = "CONVERTING FROM TIME TO FREQ DOMAIN"
     S2$ = "CONVERTING FROM FREQUENCY TO TIME DOMAIN"
     IF R = 3 THEN
    PRINT "NO CAN DO"
    GOTO 3000
END IF
     IF ISIGN = 1 THEN PRINT S1$ ELSE PRINT S2$
     FOR i = 1 TO nn * R
    FOR J = 1 TO c + 1
        INPUT #1, VALU(i, J)
    NEXT J
     NEXT i
     CLOSE #1
     IF R = 1 THEN DELTA = 1 / nn / (VALU(2, 1) - VALU(1, 1))
     IF R = 2 THEN DELTA = 1 / nn / (VALU(3, 1) - VALU(1, 1))
     'STRIP DATA
     FOR JJ = 2 TO c + 1
    CC = 1
    FOR i = 1 TO nn * 2 STEP 2
           VALS(i) = VALU(CC, JJ)
        IF R = 1 THEN VALS(i + 1) = 0 ELSE VALS(i + 1) = VALU(i
```

```
+ 1, JJ)
          CC = CC + R
     NEXT i
     CC = 1

     'GO TO FFT SUBROUTINE
CALL CONVERT(VALS!(), nn%)

     'REPLACE DATA (UNSTRIP)
     FOR i = 1 TO nn * 2
          VALU(i, JJ) = VALS(i)
     NEXT i
     'GET MAGNITUDE DATA
     FOR i = 1 TO nn * 2 STEP 2
          VALM(CC, JJ) = SQR(VALS(i) * VALS(i) + VALS(i + 1) *
VALS(i + 1))
          CC = CC + 1
     NEXT i
     NEXT JJ
     '
     'DATA STORAGE ROUTINE
     'DATA STORED IN TWO SEPARATE FILES BASED ON THE ORIGI-
NAL FILE NAME
     'THE TWO FILES WILL BE AS FOLLOWS:
     '  (1) NAME.TSD (TIME-SPLIT DATA) OR NAME.FSD (FREQUENCY
SPLIT DATA)
     '& (2) NAME.TMD (TIME MAGNITUDE DATA) OF NAME.FMD (FREQ
MAG DATA)
     '
     'STEP 1: CONVERT FIRST COLUMN (TIME <--> FREQUENCY)
     VALM(1, 1) = 0
     VALU(1, 1) = 0
     VALU(2, 1) = 0
     QTY = DELTA
     CC = 2
     FOR i = 3 TO 2 * nn STEP 2
     VALU(i, 1) = QTY
     VALU(i + 1, 1) = QTY
     VALM(CC, 1) = QTY
     QTY = QTY + DELTA
     CC = CC + 1
     NEXT i
     '
     'STEP 2: STORE DATA
     IF ISIGN = 1 THEN EXT1$ = "-FM.DAT" ELSE EXT1$ =
"-TM.DAT"
     IF ISIGN = 1 THEN EXT2$ = "-FS.DAT" ELSE EXT2$ =
"-TS.DAT"
     OPEN "\LELLO\FFT\" + ND$ + EXT2$ FOR OUTPUT AS #2
```

```
    OPEN "\LELLO\FFT\" + ND$ + EXT1$ FOR OUTPUT AS #3
    PRINT #2, nn; c; 2; ISIGN * (-1)
    PRINT #3, nn; c; 3; ISIGN * (-1)
    FOR i = 1 TO nn * 2
    FOR J = 1 TO c + 1
        PRINT #2, VALU(i, J);
    NEXT J
    PRINT #2,
    NEXT i
    CLOSE #2
    FOR i = 1 TO nn
    FOR J = 1 TO c + 1
        PRINT #3, VALM(i, J);
    NEXT J
    PRINT #3,
    NEXT i
    CLOSE #3
3000 END SUB

SUB FINDERR STATIC
PRINT "IBFIND ERROR"
END SUB

SUB FRUN (dvm%, File$, X, Y, Z, PsiL)

' This subroutine performs the voltage scan on the hot wire for
' conversion to velocities. Two channels are scanned consecutively
' with the HP44702B and the FET Multiplexer. The FET is connected
' internally to the HP44702B via a ribbon cable.

CLS
'DIM chanl(2047) AS SINGLE, chan2(2047) AS SINGLE
DIM chanl(512) AS SINGLE, chan2(512) AS SINGLE
DEFINT I-M
'*********************************************************************
*****
INPUT "Update probe info (SN, Z, PL, b & bl vectors, kl, k2,
Temp) ? ", yn$
IF yn$ = "y" THEN
    OPEN "c:\lello\dat\Probe.dat" FOR OUTPUT AS #1
INPUT "Vertical distance from test section ceiling to probe tip? ",
Z
Z = 4.55 - Z
INPUT "Horizontal distance from mount tube to probe tip? ", PL
PRINT : INPUT "Enter b vector from probe calibration: ", al, bl, cl
PRINT : INPUT "Enter bl vector: ", a2, b2, c2
PRINT : INPUT "Enter kl, k2, TempF: ", kl, k2, TF
PRINT #1, sn$, Z, PL: PRINT #1, al, bl, cl: PRINT #1, a2, b2, c2
PRINT #1, kl, k2, TF: CLOSE #1
END IF
    OPEN "c:\lello\dat\Probe.dat" FOR INPUT AS #1
```

```
INPUT #1, sn$, Z, PL: INPUT #1, a1, b1, c1: INPUT #1, a2, b2, c2
INPUT #1, k1, k2, TF: CLOSE #1
PRINT "Current probe is", sn$, ", Reference temp is", TF, "degF"
PRINT "Z plane is", Z, "PL is", PL

COLOR 0, 3
CALL SECFLO(dvm%, sfa!, sfT!)
DO ' ------------------------------------- Frequency Menu
---------------
CLS : LOCATE 10, 3: PRINT "Frequency Menu": PRINT STRING$(80,
"*")
PRINT : PRINT "      1) Update Probe XY Position"
    PRINT "      2) Begin Frequency Scan"
    PRINT "      3) Compute Avg U and Beta for a Frequency
Scan File"
    PRINT "      4) Return to Main Menu"
choice$ = INPUT$(1)
SELECT CASE choice$
    CASE "1": CALL locatn(File$, PL, Z, X, Y, Psi)
    CASE "2": CLS : LOCATE 10, 7
LOCATE 7, 7
INPUT "Use the same root filename as in MAIN ? ", ans$
IF ans$ <> "y" THEN
    CLS : LOCATE 7, 7: INPUT " Input the new file name ", File$
END IF
PRINT : PRINT "             Press any key to initiate scan"
DO: LOOP WHILE INKEY$ = ""
CLS : LOCATE 7, 7: PRINT "Turbulence scan in progress"
'**********************************************************   Read
hotwires
CALL IBWRT(dvm%, "RST 400")
CALL IBWRT(dvm%, "USE 400")
'CALL IBWRT(dvm%, "REAL WAVE(4095),OUT1(2047),OUT2(2047)")
CALL IBWRT(dvm%, "REAL WAVE(1024),OUT1(512),OUT2(512)")
CALL IBWRT(dvm%, "DISP OFF")
'*****************************************************************
*
'Configure the HP44702B for  high-speed scanning.

CALL IBWRT(dvm%, "SCANMODE ON;CONF DCV;ARMODE BEFORE")
CALL IBWRT(dvm%, "TERM RIBBON;range 9;RDGSMODE COMPLETE")
CALL IBWRT(dvm%, "SCDELAY 0")
CALL IBWRT(dvm%, "SPER 10E-6")
'CALL IBWRT(dvm%, "PRESCAN 2048;POSTSCAN 0")
CALL IBWRT(dvm%, "PRESCAN 512;POSTSCAN 0")
CALL IBWRT(dvm%, "CLWRITE SENSE,321-322;ASCAN ON;SCTRIG SGL")
'CALL IBWRT(dvm%, "XRDGS 400, 4096 INTO WAVE")     'Trigger the
scan
CALL IBWRT(dvm%, "XRDGS 400, 1024 INTO WAVE")     'Trigger the
scan
```

```
'******************************************************************
CALL IBWRT(dvm%, "SUB SEPARAT")   'Separate the readings into 2
arrays
CALL IBWRT(dvm%, "INTEGER I,J")
CALL IBWRT(dvm%, "J = 0")
'CALL IBWRT(dvm%, "FOR I = 0 TO 4095 STEP 2")
CALL IBWRT(dvm%, "FOR I = 0 TO 1023 STEP 2")
CALL IBWRT(dvm%, "OUT1(J) = WAVE(I)")
CALL IBWRT(dvm%, "OUT2(J) = WAVE(I+1)")
CALL IBWRT(dvm%, "J = J+1")
CALL IBWRT(dvm%, "NEXT I")
CALL IBWRT(dvm%, "SUBEND")
'******************************************************************

CLS : LOCATE 7, 7: PRINT "Processing Data"
'******************************************************************
CALL IBWRT(dvm%, "CALL SEPARAT")
CALL IBWRT(dvm%, "SCTRIG HOLD")
'******************************************************************
CLS : LOCATE 7. 7: PRINT "Writing data to temporary disk storage"
'******************************************************************
'Transfer all readings to the computer controller.

CALL IBWRT(dvm%, "VREAD OUT1")
CALL IBRDF(dvm%, "C:\LELLO\FREQ1.DAT")
CALL IBWRT(dvm%, "VREAD OUT2")
CALL IBRDF(dvm%, "C:\LELLO\FREQ2.DAT")

'Read from temporary files into memory.
OPEN "C:\LELLO\FREQ1.DAT" FOR INPUT AS #3
OPEN "C:\LELLO\FREQ2.DAT" FOR INPUT AS #4
    FOR i = 0 TO 511                                '2047
        INPUT #3, chan1(i)
        INPUT #4, chan2(i)
    NEXT i
CLOSE #3
CLOSE #4
'******************************************************************
**
dir$ = "A:\" + "TU" + File$ + ".dat"
CLS : LOCATE 7, 7: PRINT "Writing data to :", dir$
OPEN dir$ FOR OUTPUT AS #1
PRINT #1, X, Y, Z, PsiL, "X,Y,Z & PsiL "
time! = 0!
FOR i = 0 TO 511                                    '2047
PRINT #1, time!, chan1(i), chan2(i)
  time! = time! + .00002
NEXT i
```

```
CLOSE #1
'*********************************************************************
CALL IBWRT(dvm%, "DISP ON;RST 400")
CLS : LOCATE 7, 7
PRINT "Turbulence data acquisition completed"
LOCATE 7, 12: PRINT "Press any key to return to Frequency Menu"
    DO: LOOP WHILE INKEY$ = ""
      CASE "3": CLS : '---------------------------------- compute
U and Beta
dir$ = "A:\": PRINT "Current file is ", File$
INPUT "Select a different file? ", yn$
IF yn$ <> "y" THEN
    dirf$ = dir$ + "TU" + File$ + ".dat"
    GOTO 17
END IF
PRINT "   Current files list:": PRINT
FILES dir$ + "*.dat": PRINT
INPUT "Enter the handle (<= 5 chars.)", H$
dirf$ = dir$ + "TU" + H$ + ".dat"
nn% = 512  'nn% = 2048
17 OPEN dirf$ FOR INPUT AS #1
DIM E1(nn% - 1), E2(nn% - 1), time!(nn% - 1), beta(nn% - 1),
Uinf(nn% - 1)
DIM u(nn% - 1), v(nn% - 1), uprime(nn% - 1), vprime(nn% - 1)
FOR i = 0 TO nn% - 1: INPUT #1, time!(i), E1(i), E2(i): NEXT i
CLOSE #1 ' ------------------------------- Compute velocities
alf = pi / 4: usum = 0: betasum = 0
FOR i = 0 TO nn% - 1    'Store U1eff in E1, U2eff inE2
E1(i) = ((-b1 + SQR(b1 ^ 2 - 4 * a1 * (c1 - E1(i)^2)))/(2 * a1))^2
E2(i) = ((-b2 + SQR(b2 ^ 2 - 4 * a2 * (c2 - E2(i)^2)))/(2 * a2))^2
beta(i) = alf - ATN(SQR((k1 * E2(i) ^ 2 - E1(i) ^ 2 / k2 * E1(i)^2 -
E2(i) ^ 2)))
IF E2(i) > E1(i) THEN beta(i) = ABS(beta(i))
IF E1(i) > E2(i) THEN beta(i) = -ABS(beta(i))
Uinf(i) = SQR(E1(i) ^ 2 / ((COS(alf + beta(i))) ^ 2 + k1 * SIN(alf +
beta(i))) ^ 2)
usum = usum + Uinf(i): betasum = betasum + beta(i)
PRINT E1(i), E2(i), Uinf(i), beta(i)
NEXT i
' ---------------------------------------- Output file choice
PRINT "Computation complete."
umean = usum / nn%: betamean = betasum / nn%
PRINT "Avg velocity: ", umean, "Avg beta: ", betamean
INPUT "Compute u/v rms, turb, etc  & write all to file? ", yn$
IF yn$ = "y" THEN
    u(i) = Uinf(i) * COS(beta(i))
    v(i) = Uinf(i) * SIN(-beta(i))
    usum = 0: vsum = 0
```

```
     FOR i = 0 TO nn% - 1
    usum = usum + u(i): vsum = vsum + ABS(v(i))
     NEXT i
    umean = usum / nn%: vmean = vsum / nn%
    usum = 0: vsum = 0
     FOR i = 0 TO nn% - 1
    uprime(i) = u(i) - umean: usum = usum + (uprime(i) ^ 2)
    vprime(i) = v(i) - umean: vsum = vsum + (vprime(i) ^ 2)
     NEXT i
    urms = SQR(usum / nn%): vrms = SQR(vsum / nn%)
    turbint = urms / umean
    turbmean = SQR(((urms/umean)^2 + (vrms/umean)^2)/2) * 100
     INPUT "Write to different file designator?", yn$
     IF yn$ = "y" THEN
         INPUT "New file designator? ", H$
         dirf$ = dir$ + H$ + ".vel"
     ELSE dirf$ = dir$ + File$ + ".vel"
     END IF
    PRINT "Velocity info is being stored in ", dirf$
    OPEN dirf$ FOR OUTPUT AS #2
    PRINT #2, "Velocity Data for   ", File$
    PRINT #2, "Uinf avg:", umean, "Beta avg:", betamean
    PRINT #2, "u rms:", urms, "v rms", vrms
    PRINT #2, "Turb int:", turbint, "Turb avg", turbmean
    INPUT "Write time/u'/v' to this file?", yn$
    IF yn$ = "y" THEN
        FOR i = 0 TO nn% - 1
        PRINT #2, time(i), uprime(i), vprime(i): NEXT i
    END IF
    CLOSE #2

END IF
     CASE "4": CLS : EXIT DO
     CASE ELSE: BEEP
END SELECT
LOOP
END SUB

DEFSNG I-M
SUB GPIBERR STATIC
PRINT "GPIB ERROR"
END SUB

SUB locatn (File$, PL, Z, X, Y, PsiL)
'This routine takes three angle values (alfa,beta,gamma) and the
horizontal
'probe length (if any), and computes the probe tip location and
bisector
'angle (from X axis) in the test section reference frame.  This
```

```
requires
'a home point in terms of two angles (betah and gammah) for
vector addition.
'     X,Y, Z, and PsiL are stored permanently in A:\runlocn.dat
'next to the FileName of the particular run.  Z=0 Plane is the floor
of
'the test section; accuracy is < .1 inch.  Index arm length is L
(inches).
'                Written by Capt Acree, 8/90
L = 10: rpd = .0174533: dpr = 57.29578: pi = 3.14159
CLS : LOCATE 3, 7: PRINT "XYPsi Location Program, written by
Capt Acree 7/90"
SLEEP 4
DO
    CLS : LOCATE 3, 7: PRINT "Locator Menu"
    PRINT STRING$(80, "-"): PRINT
    PRINT "1)  Compute X,Y (inches) and PsiL for probe location"
    PRINT "2)  Enter HOME POINT angles"
    PRINT "3)  Return to Frequency Menu"
    PRINT : PRINT "TYPE YOUR SELECTION (1-3)": CH$ = INPUT$(1)
    SELECT CASE CH$
CASE "3": EXIT DO
CASE "2"    '------------------------------- record Home Point
    CLS : LOCATE 7, 7
    PRINT "Place the probe mount over the HOME POINT."
    PRINT "Measure the angle between the first index arm and the
Y axis."
    INPUT "GammaH (CW) in degrees is: ", gamH: PRINT
    PRINT "Measure the acute angle between the index arms."
    INPUT "BetaH (CCW) in degrees is: ", betaH: PRINT
    gamH = gamH * rpd: betaH = betaH * rpd
    HX = L * SIN(gamH) + L * COS(betaH - gamH - (pi / 2))
    HY = L * COS(gamH) + L * SIN(betaH - gamH - (pi / 2))
    PRINT "Home is ", HX, HY
    OPEN "C:\lello\data\homexy.dat" FOR OUTPUT AS #1
    PRINT #1, HX, HY: CLOSE #1
    OPEN "A:\runlocn.dat" FOR APPEND AS #2
    PRINT #2, "New HOME:", HX, HY: CLOSE #2: SLEEP 5
CASE "1"  '-------------------------------- Current location
    CLS
    OPEN "C:\LELLO\DATA\HOMEXY.dat" FOR INPUT AS #1
    INPUT #1, HX, HY: CLOSE #1
    INPUT "Gamma in degrees is: ", gam
    INPUT "Beta in degrees is: ", beta
    INPUT "Alpha (CW from index arm 2) in degrees is: ", alfa
    gam = gam * rpd: beta = beta * rpd: alfa = alfa * rpd
    phi0 = beta - (pi / 2) - gam
    phil = (pi / 2) - gam + beta - alfa
```

```
    AX = L * SIN(gam) + L * COS(phi0) + PL * COS(phil)
    AY = L * COS(gam) + L * SIN(phi0) + PL * SIN(phil)
    X = AX - HX: Y = AY - HY
    PsiL = phil
    OPEN "A:\runlocn.dat" FOR APPEND AS #1:
    PRINT #1, File$, X, Y, Z, PsiL: CLOSE #1
    PRINT "x,y,z in inches:"; X, Y, Z
    PRINT "PsiL is ", PsiL * dpr, "degrees CW from X axis"
    PRINT "Hit any key to return to main menu"
    DO: LOOP WHILE INKEY$ = ""
CASE ELSE: BEEP
END SELECT
LOOP
END SUB

SUB PLOTT (xdat() AS SINGLE, ydat() AS SINGLE, xmin!, xmax!,
ymin!, ymax!, xlab$, ylab$, pltlab$, ntot%)
'*******************************************************************

'this section of the code creates a plot of ydat vs xdat
CLS
SCREEN 9  'Hi-res graphics mode
VIEW (120, 10)-(570, 290), , 1
WINDOW (xmin!, ymin!)-(xmax!, ymax!)
style% = &HFF00
LOCATE 23, 42: PRINT pltlab$
LOCATE 1, 9: PRINT ymax!: LOCATE 10, 7
PRINT ylab$: LOCATE 21, 9: PRINT ymin!
LOCATE 22, 14: PRINT xmin!: LOCATE 22, 43
PRINT xlab$: LOCATE 22, 71: PRINT xmax!
VIEW PRINT 24 TO 25:
    PRINT SPC(14); , "hit any key to return to Main Menu"

    CLS
    LINE (1, 0)-(0, 0), , , style%
        FOR i = 1 TO ntot%
            X = xdat(i)
            Y = ydat(i)
            LINE -(X, Y)
        NEXT i
DO: LOOP WHILE INKEY$ = ""
CLS
SCREEN 0: COLOR 3, 0

END SUB

SUB PRUN (dvm%, rho!, dt$, File$, iflag%, T!, q!)
```

```
'********************************************************************
**
' A scanivalve driver program for the HP 3852A data acquisition
system.
' Programmed by  Lt Galassi 6/21/89, modified by Capt A    /90
'  This subroutine performs a pressure scan on the turbine blade
'  using the HP3852A data acquisition system to drive a scanivalve
'  step motor over 30 pressure ports.
'
' The ports are assigned as follows:
'
'       port 0          atmospheric
'            1-10       blade static
'            11         atmospherric
'            12-21      blade static
'            22         atmospheric
'            23,24,25   blade static
'            26         pitot head
'            27         atmospheric
'            28         pitot static
'            29-36      atmospheric
'________________________________________________________________________
__

SHARED chord()  AS SINGLE
DEFINT I-M


DIM xdat(23) AS SINGLE, ydat(23)  AS SINGLE
DIM pscan(30) AS SINGLE
CLS 2
IF iflag% = 1 THEN
  INPUT "File name to store Cp data ? ", File$
END IF
  iflag% = 1


OPEN "A:\CP\" + "CP" + File$ + ".cp" FOR OUTPUT AS #1
OPEN "A:\CP\" + "GR" + File$ + ".DAT" FOR OUTPUT AS #3'GRAPHER
output file
CLS
'CALL TMON(dvm%)
SLEEP 4
COLOR 0, 3: LOCATE 7, 7
PRINT "Secondary flow on ?": DO: LOOP WHILE INKEY$ = ""
IF INKEY$ = "y" THEN
    CLS : LOCATE 7, 7
```

```
    CALL SECFLO(dvm%, sfa!, sfT!)
    PRINT "Secondary flow pressure  (kPa) = ", sfa!
    PRINT "Secondary flow temperature (C) = ", sfT!
ELSE : sfa! = 0
END IF

LOCATE 8, 7: PRINT "      BLADE PRESSURE SURVEY (approx 115
sec. duration)"
'****************************  set up the HP44701 for voltage
measurements

CALL IBWRT(dvm%, "RST 600")
WRT$ = "REAL A(1),B(1), PSCAN(30),OUTPUT(30),C(49),L,H,M,S"
CALL IBWRT(dvm%, WRT$)

'  Arrays are designated as follows:
'
' A - voltages from the pressure transducer calibration (SCANCAL
pgm).
'       Use largest voltages (i.e., the endpoints of the calibration).
' B - corresponding pressures to the voltages listed in array A.
' PSCAN - actual pressures in KPa units
' OUTPUT - a temporary holding array for HP3852 buffer.

CALL IBWRT(dvm%, "VWRITE A,-11.734,10.000")
CALL IBWRT(dvm%, "VWRITE B,-8.400,10.358")

'  Perform the actual pressure scan

CALL IBWRT(dvm%, "USE 600;AZERO ONCE; NPLC 16")
CALL IBWRT(dvm%, "CLOSE 101")     'this call homes the scanivalve
CALL IBWRT(dvm%, "OPEN 101;CONF DCV")
CALL IBWRT(dvm%, "NRDGS 50")

WRT$ = "MEAS DCV, 221,INTO C"           'read atmospheric press.
CALL IBWRT(dvm%, WRT$)
CALL IBWRT(dvm%, "STAT L.H,M,S,C")
CALL IBWRT(dvm%, "PSCAN(0) = M")
CALL IBWRT(dvm%, "DISP PSCAN(0)")

CALL IBWRT(dvm%, "SUB LOOP")              'HP 3852A subroutine
CALL IBWRT(dvm%, "INTEGER I")
CALL IBWRT(dvm%, "FOR I = 1 TO 28")
CALL IBWRT(dvm%, "CLOSE 100")
CALL IBWRT(dvm%, "OPEN 100;CONF DCV;NRDGS 50")
CALL IBWRT(dvm%, "MEAS DCV, 221, USE 600, INTO C")
CALL IBWRT(dvm%, "STAT L,H,M,S,C")
CALL IBWRT(dvm%, "PSCAN(I) = M")
CALL IBWRT(dvm%, "DISP PSCAN(I)")
CALL IBWRT(dvm%, "NEXT I")
CALL IBWRT(dvm%, "SUBEND")
```

```
CALL IBWRT(dvm%, "CALL LOOP")
SLEEP 119                                 'allow 120 seconds for
scan
WRT$ = "CONV A,B,PSCAN, INTO OUTPUT"
CALL IBWRT(dvm%, WRT$)
CALL IBWRT(dvm%, "VREAD OUTPUT")
'*****************************************************************
**

'Read output into a temporary file on the hard disk

CALL IBRDF(dvm%, "C:\LELLO\PRESS.DAT")

OPEN "C:\LELLO\PRESS.DAT" FOR INPUT AS #2
FOR i = 0 TO 28
    INPUT #2, pscan(i)
NEXT i
CLOSE #2


'*****************************************************************
*
'
'  Output the data into File$
'  Array locations are assigned as follows:
         ' 0,11,22,29-36 - Atmospheric pressure
         ' 1-10,12-21,23-25  - Blade static pressures
         ' 26 -Pitot head press.
         ' 28- Pitot static press.
CLS
COLOR 0

PRINT "Pressure Measurements on Turbine Blade #2"
PRINT #1, "Pressure Measurements on Turbine Blade #2"
PRINT : PRINT "Date of run:", dt$
PRINT : PRINT #1, "Date of run:", dt$
PRINT : PRINT "Time of run:", TIMER / 3600
PRINT : PRINT #1, "Time of run:", TIMER / 3600
PRINT : PRINT #1, "Secondary flow pressure:", sfa!
PRINT : PRINT #1, "Head and static pitot press. (kPa):", pscan(26),
pscan(28)

' Note: q is in KPa

q! = pscan(26) - pscan(28)
deltah! = q! * 1000! / 248!
PRINT #1, "deltah is computed to be:", deltah!
PRINT : PRINT "The difference in height of the manometer columns"
PRINT "is computed by scanivalve measurements to be: "; deltah!
INPUT " Is this correct? (y or n) ", ans$
IF ans$ <> "y" THEN
    BEEP
```

```
    PRINT : PRINT "SCANIVALVE readings are faulty"
    PRINT "Returning to Main Menu": SLEEP 10
    CLOSE #1: CLOSE #3: COLOR 4, 11: RETURN
END IF

vel! = SQR(2000! * q! / rho!)
PRINT : PRINT "Freestream velocity (m/sec): "; vel!

nu! = 1.144E-05 + (T! + 23.15) * 9.48E-06 / 100!

Re! = vel! * .114 / nu!
PRINT "Reynold's no. = ", Re!
PRINT : PRINT #1, "Freestream velocity (m/sec):", vel!
PRINT #1, "Reynold's number :", Re!: SLEEP 5

' Perform shift on PSCAN() to collapse the vector.
'This technique is recommended by the Scanivalve manufacturer to
help
'identify step motor miscues.
FOR i = 11 TO 20
   pscan(i) = pscan(i + 1)
NEXT i
FOR i = 21 TO 23
   pscan(i) = pscan(i + 2)
NEXT i

PRINT STRING$(70, "_")
PRINT #1, STRING$(70, "_")
PRINT #1, " Port No.      CHORD LOCATION   Pstatic    Cp"

LOCATE 8, 1
PRINT " CHORD LOCATION", SPACE$(12), "Cp"

LOCATE 9, 1
PRINT STRING$(80, "_")
LOCATE 22, 1
PRINT STRING$(80, "_")
VIEW PRINT 8 TO 20
CLS 2


FOR i = 1 TO 10
  PRINT i, chord(i), pscan(i), (pscan(i) - pscan(28)) / q!
  PRINT #1, i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28))
/ q!
  PRINT #3, i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28))
/ q!

NEXT i
```

```
PRINT "        Hit any key to continue"
DO: LOOP WHILE INKEY$ = ""
FOR i = 11 TO 20
  PRINT i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28)) /
q!
  PRINT #1, i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28))
/ q!
  PRINT #3, i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28))
/ q!
NEXT i

PRINT "        Hit any key to continue"
DO: LOOP WHILE INKEY$ = ""
FOR i = 21 TO 23
  PRINT i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28)) /
q!
  PRINT #1, i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28))
/ q!
  PRINT #3, i, chord(i), pscan(i) - pscan(28), (pscan(i) - pscan(28))
/ q!

NEXT i
PRINT "Hit any key to continue"
DO: LOOP WHILE INKEY$ = ""

'This section drives the plotter.

ntot% = 23    'This no. corresponds to the total no. of suction
ports
'ntot2% = 14    'This no. corresponds to the total no. of pressure
ports
ylab$ = "Cp"
xlab$ = "x/c"
pltlab$ = "Cp on the turbine blade"
xmin! = 0!
xmax! = 1!
ymin! = -4.5
ymax! = 4.5

FOR i = 1 TO ntot%
 ydat!(i) = (pscan(i) - pscan(28)) / q
 xdat!(i) = chord(i)
NEXT i


CALL PLOTT(xdat!(), ydat!(), xmin!, xmax!, ymin!, ymax!, xlab$,
ylab$, pltlab$, ntot%)

CLOSE #1: CLOSE #3
CALL IBWRT(dvm%, "RST")
END SUB
```

```
DEFSNG I-M
SUB SECFLO (dvm%, sfa!, sfT!)

'Measure the secondary flow manifold pressure
PRINT "  Measuring Secondary Flow Pressure and Temperature"
CALL IBWRT(dvm%, "REAL P1(1),V1(1),V2(1),OUTPUT(1)")
CALL IBWRT(dvm%, "vwrite V1,.000,.319")
CALL IBWRT(dvm%, "vwrite P1, 0.000,633.6505")
CALL IBWRT(dvm%, "RST 600;USE 600; AZERO ONCE;NPLC 16")
CALL IBWRT(dvm%, "CONFMEAS DCV,222,INTO V2")
CALL IBWRT(dvm%, "DISP V2(0)")
CALL IBWRT(dvm%, "CONV V1,P1,V2,INTO OUTPUT")
CALL IBWRT(dvm%, "VREAD OUTPUT(0)")
rd$ = SPACE$(16)
CALL ibrd(dvm%, rd$)
sfa! = VAL(rd$)
CALL IBWRT(dvm%, "RST 600;USE 600;REAL T; AZERO ONCE;")
CALL IBWRT(dvm%, "CONFMEAS TEMPJ,021,INTO T")
CALL IBWRT(dvm%, "VREAD T")
rd$ = SPACE$(16)
CALL ibrd(dvm%, rd$)
sfT! = VAL(rd$)

CLS : LOCATE 7, 7
PRINT "Secondary pressure  (kPa) =", sfa!
PRINT "Secondary temperature (C) =", sfT!
PRINT : PRINT "Press any key to continue"
DO: LOOP WHILE INKEY$ = ""
CLS
END SUB

SUB TMON (dvm%)
'**********************************************************************
**

'Configure the HP3852 to sense blade temperature

CALL IBWRT(dvm%, "USE 600;RST 600;REAL T;AZERO ONCE")
CALL IBWRT(dvm%, "CLOSE 104")
CALL IBWRT(dvm%, "CONFMEAS TEMPJ,210, INTO T")
CALL IBWRT(dvm%, "OPEN 104")
'**********************************************************************
**
'Read datum from HP3852

CALL IBWRT(dvm%, "DISP T")
CALL IBWRT(dvm%, "VREAD T")
rd$ = SPACE$(16)
CALL ibrd(dvm%, rd$)
```

```
'*******************************************************************
**
T! = VAL(rd$)          'convert the string value into a
                   'number
CLS
LOCATE 7, 7
PRINT "Blade Temperature (F) is currently: ", (T! * 9! / 5!) + 32!
PRINT : PRINT
IF T! > 65.56 THEN
    CALL IBWRT(dvm%, "CLOSE 104")           'this call turns
power
                              ' supply off.
    BEEP: SLEEP 1: BEEP: SLEEP 1: BEEP
    PRINT "Blade temperature too high!": PRINT
    PRINT "Check Power Supply": PRINT
    PRINT " Press any key to continue"
    DO: LOOP WHILE INKEY$ = ""
    CALL IBWRT(dvm%, "open 104")
    CLS 2
END IF
LOCATE 8, 7
PRINT "Press any key to continue"
DO: LOOP WHILE INKEY$ = ""
CLS
END SUB
SUB Troom (dvm%, T!)
'*******************************************************************
**
'Configure the HP3852 to sense room temperature on Channel 020
(wire 30)
CALL IBWRT(dvm%, "USE 600;RST 600;REAL T;AZERO ONCE")
CALL IBWRT(dvm%, "CONFMEAS TEMPJ,020, INTO T")
'*******************************************************************
**
'Read datum from HP3852
CALL IBWRT(dvm%, "DISP T")
CALL IBWRT(dvm%, "VREAD T")
rd$ = SPACE$(16)
CALL ibrd(dvm%, rd$)
'*******************************************************************
**
T! = VAL(rd$)          'convert the string value into a number
CLS : LOCATE 7, 7
PRINT "Room Temperature (F) is currently: ", (T! * 9! / 5!) + 32!
PRINT : PRINT : LOCATE 8, 7
PRINT "Press any key to return to main menu."
```

```
DO: LOOP WHILE INKEY$ = ""
CLS
END SUB

SUB TRUN (dvm%, T!, File$, rho!, q!)
'*******************************************************************
**

'This subroutine performs the temperature scan on the turbine
blade
'and stores the data in A:/heat/File$.dat. The HP3852 is used to
'acquire data through the HP 44713A FET Multiplexers.

DIM nu(28) AS SINGLE
DIM rhol(28) AS SINGLE
DIM t2scan(31) AS SINGLE
DIM deltal(23) AS SINGLE
DIM deltaT(23) AS SINGLE
DIM Resistivity(23) AS SINGLE
DIM vel(23) AS SINGLE
DIM S(23) AS SINGLE
DIM Nslt(23) AS SINGLE
DIM St(23) AS SINGLE
DIM xdat!(23), ydat!(23)

SHARED chord()  AS SINGLE
DEFINT I-M
'*******************************************************************
CALL TMON(dvm%)
'*******************************************************************
'Read the blade temperatures, and Ttunnel and Troom.
'The first 16 Tcouples (wire #s 1-16) are on slot 2 (Channels
201-216),
'and the next 16 (wire #s 17-32) are on slot 0 (Channels 007-022).

CALL IBWRT(dvm%, "RST 600; AZERO ONCE;NPLC 1")
CALL IBWRT(dvm%, "SUB TBLADE")
CALL IBWRT(dvm%, "REAL A(31)")
CALL IBWRT(dvm%, "CLOSE 104")          'current off
CALL IBWRT(dvm%, "CONFMEAS TEMPJ,201-216,007-021,INTO A")
CALL IBWRT(dvm%, "OPEN 104")           ' current on
CALL IBWRT(dvm%, "VREAD A")
CALL IBWRT(dvm%, "SUBEND")

'*******************************************************************
**
DO

' Interactive input for the power parameters on the turbine blade.
```

```
CLS : LOCATE 7, 7
PRINT "Is the tunnel q still", q! / .248, "inches? (y/n)"
DO: LOOP WHILE INKEY$ = ""
IF INKEY$ = "n" THEN
    INPUT "Input the q of the tunnel in inches of water: ", del-
tah!
    q! = deltah! * 248                              'Convert to kPa
END IF
Vinf! = SQR(2000! / rho! * q!)
    LOCATE 9, 7
    PRINT " The freestream velocity is "; Vinf!; " m/s"
    SLEEP 3

CLS : LOCATE 7, 7
INPUT "Blade power supply current in amps ? ", Curr!
IF Curr! = 0! THEN Curr! = .001
'measured foil area = 0.26352 m x 0.0508 m
ATot! = .013387      '= area of foil (m^2)

CLS : LOCATE 7, 7
PRINT "Is the secondary injection on ? ": DO: LOOP WHILE INKEY$
= ""
IF INKEY$ = "y" THEN
    CALL SECFLO(dvm%, sfa!, sfT!)
ELSE
    sfa! = 0!
END IF
'*****************************************************************

CLS : LOCATE 3, 7: PRINT "Temperature Scan Menu"
PRINT STRING$(80, "_"): PRINT
PRINT "1) Temperature Scan"
PRINT
PRINT "2) EXIT"
PRINT : PRINT "type your selection (1-2)"
chs$ = INPUT$(1)

SELECT CASE chs$

CASE "1"
    CLS : LOCATE 7, 7
    'Turbulence ON temperature scan on the blade

    PRINT "Press any key to initiate scan"
    DO: LOOP WHILE INKEY$ = ""
    CALL IBWRT(dvm%, "DISP OFF")
    CALL IBWRT(dvm%, "CALL TBLADE")
    CALL IBRDF(dvm%, "A:\heat\T" + File$ + ".DAT")
    CALL IBWRT(dvm%, "DISP ON")
'******************************************************************
```

```
'Read data from storage

OPEN "A:\heat\T" + File$ + ".DAT" FOR INPUT AS #1
    FOR i = 1 TO 31
        INPUT #1, t2scan(i)
    NEXT i
CLOSE #1
tinf = t2scan(29)'Use tunnel temperature as Tfreestream
PRINT "tunnel temp:", tinf, "Secondary temp:"; t2scan(31): SLEEP 5
FOR i = 1 TO 15: PRINT i, t2scan(i): NEXT i: SLEEP 5
FOR i = 16 TO 30: PRINT i, t2scan(i): NEXT i: SLEEP 5
'*****************************************************************

'Read in the Pressure Coefficients on the blade
'to be used in computation of Nusselt and Stanton numbers.

OPEN "a:\cp\gr" + File$ + ".dat" FOR INPUT AS #1

vel(0) = 0!
FOR i = 1 TO 23
    INPUT #1, dummy, dummy, dummy, vel(i)
NEXT i
CLOSE #1

'read in thermocouple distances along the blade surface S()

OPEN "C:\lello\data\S.dat" FOR INPUT AS #1

FOR i = 1 TO 23
    INPUT #1, S(i)
NEXT i
CLOSE #1
'*****************************************************************
'perform energy balance calculations

'conduction constants
uk! = .026      'urethane foam thermal conductivity, (W/m*K)
ak! = .0263     'air thermal conductivity (W/m*K) at 30 C

'convection constants
Cp! = 1000.5    'for air at 30 C, (J/kg*K)
Pr! = .707

'compute nu(i) and rhol(i) on the blade
FOR i = 0 TO 28
    nu(i) = 1.144E-05 + ((t2scan(i) + tinf!)/2! + 23.15)*9.48E-06/100!
    rhol(i) = 1.3947 - .3797 * ((t2scan(i) + tinf!)/2! + 23.15)/100!
NEXT i

'radiation constants
eps! = .17         'emissivity for polished stainless steel at 300 K
sigma! = 5.67E-08  'Stefan-Boltzmann constant, (W/m^2*K^4)
```

```
'compute local velocities on the blade (m/s)
FOR i = 1 TO 23
    vel(i) = SQR((Vinf! ^ 2) * ABS(1! - vel(i)))
NEXT i

'Compute local Reynolds numbers on the blade (based on distance
from
' leading edge).  Compute local resistivity of the foil.
FOR i = 1 TO 23
vel(i) = vel(i) * S(i) / nu(i)
Resistivity(i) = 2.223*10^-10 * (t2scan(i)*1.8+32) + 8.446*10^-7
    'ohm-m
NEXT i

'compute the Nusselt and Stanton numbers for the blade, using
'steady-state 2-D heat model (ignore spanwise and chordwise heat
'conduction through the steel foil as << heat convection).

FOR i = 0 TO 23                        'clean the arrays
    Nslt(i) = 0!
    St!(i) = 0!

NEXT i
'Read file of deltal distances between Tcouples:
OPEN "C:\lello\DATA\DELTAL.DAT" FOR INPUT AS #3
    FOR i = 1 TO 23
        INPUT #3, deltal(i)
    NEXT i
CLOSE #3
'Construct deltaT(i), the internal temp differences
    FOR i = 1 TO 3
        deltaT(i) = t2scan(i) - t2scan(24)
    NEXT i
    FOR i = 22 TO 23
        deltaT(i) = t2scan(i) - t2scan(24)
    NEXT i
    deltaT(4) = t2scan(4) - t2scan(25)
    deltaT(5) = t2scan(5) - t2scan(26)
    deltaT(6) = t2scan(6) - t2scan(15)
    deltaT(7) = t2scan(7) - t2scan(27)
    deltaT(8) = t2scan(8) - t2scan(28)
    deltaT(9) = t2scan(9) - t2scan(12)
    deltaT(10) = t2scan(10) - t2scan(12)
    deltaT(11) = t2scan(11) - t2scan(28)
    deltaT(12) = t2scan(12) - t2scan(9)
    deltaT(13) = t2scan(13) - t2scan(28)
    deltaT(14) = t2scan(14) - t2scan(7)
    deltaT(15) = t2scan(15) - t2scan(27)
    deltaT(16) = t2scan(16) - t2scan(6)
    deltaT(17) = t2scan(17) - t2scan(26)
    deltaT(18) = t2scan(18) - t2scan(26)
```

```
    deltaT(19) = t2scan(19) - .5 * (t2scan(25) + t2scan(26))
    deltaT(20) = t2scan(20) - .5 * (t2scan(25) + t2scan(26))
    deltaT(21) = t2scan(21) - t2scan(25)
IF Curr! = 0 THEN 400
OPEN "a:\heat\ht" + File$ + ".dat" FOR OUTPUT AS #2
Qheat! = Curr! ^ 2 * .1018          'Watts
PRINT #2, "File:"; SPC(1); File$
PRINT "Secondary flow pressure = "; SPC(1); sfa!; SPC(2); "KPa"
PRINT #2, "Secondary flow pressure = "; SPC(1); sfa!; SPC(2);
"KPa"
PRINT #2, "Secondary flow temperature (C) = "; SPC(1); t2scan(31)
PRINT #2, "Electrical energy input = "; SPC(1); Qheat!; SPC(1);
"Watts"
    PRINT #2, "node", "deltaT", "deltal", "resistivity"
    PRINT #2, " ", "Conductn", "Radiation", "I2R/m2", "h"

FOR i = 1 TO 2    'Use Stagnation on Round-nose Blunt body
    rad = .005                           'radius of blunt nose,
m
    vel(i) = vel(i) * rad / S(i)          'convert ReS to ReR
    Nslt(i) = .81 * ((vel(i)) ^ .5) * (Pr! ^ .4)
    St(i) = Nslt(i) / (Pr! * vel(i))
NEXT i

FOR i = 3 TO 10                                   'Pressure
side
    F1! = uk! * deltaT(i) / deltal(i)
    F2! = eps! * sigma! * (t2scan(i) ^ 4 - tinf! ^ 4)
    F3! = (t2scan(i) - tinf!)
    Qheat! = Curr! ^ 2 * Resistivity(i) * 7628 * 10 ^ 3     'W/m^2
    H! = (Qheat! - F1! - F2!) / F3!
    PRINT #2, i, deltaT(i), deltal(i), Resistivity(i)
    PRINT #2, " ", F1!, F2!, Qheat, H!
    Nslt(i) = ABS(H!) * S(i) / ak!
    St(i) = Nslt(i) / (Pr! * vel(i))
NEXT i
'Node 11 has no heat generation term since it is off the foil.
    F1! = uk! * deltaT(11) / deltal(11)
    F2! = eps! * sigma! * (t2scan(11) ^ 4 - tinf! ^ 4)
    F3! = (t2scan(11) - tinf!)
    H! = (-F1! - F2!) / F3!
    Nslt(11) = ABS(H!) * S(11) / ak!
    St(11) = Nslt(11) / (Pr! * vel(11))

FOR i = 12 TO 23                                  'Suction side
    F1! = uk! * deltaT(i) / deltal(i)
    F2! = eps! * sigma! * (t2scan(i) ^ 4 - tinf! ^ 4)
    F3! = (t2scan(i) - tinf!)
    Qheat! = Curr! ^ 2 * Resistivity(i) * 7628 * 10 ^ 3    'W/m^2
    H! = (Qheat! / ATot! - F1! - F2!) / F3!
```

```
    PRINT #2, i, deltaT(i), deltaI(i), Resistivity(i)
    PRINT #2, " ", F1!, F2!, Qheat!, H!
    Nslt(i) = ABS(H!) * S(i) / ak!
    St(i) = Nslt(i) / (Pr! * vel(i))
NEXT i
'CLOSE #2
'*****************************************************************
*
400
'save data on disk
CLS : LOCATE 1, 10: PRINT "Temperature output"
PRINT
Qheat! = Curr! ^ 2 * .1018          'Watts
'OPEN "A:\HEAT\" + "HT" + File$ + ".DAT" FOR APPEND AS #2
'PRINT #2, "File:"; SPC(1); File$
'PRINT "Secondary flow pressure = "; SPC(1); sfa!; SPC(2); "KPa"
'PRINT #2, "Secondary flow pressure = "; SPC(1); sfa!; SPC(2);
"KPa"
'PRINT #2, "Secondary flow temperature (C) = "; SPC(1); t2scan(31)
'PRINT #2, "Electrical energy input = "; SPC(1); Qheat!; SPC(1);
"Watts"
PRINT #2, "          Heat Transfer Summary"
PRINT , "Tap#", "x/c", "Re no.", "Nusselt", "Stanton"
PRINT #2, "Tap#", "x/c", "Re no.", "Nusselt", "Stanton"
FOR i = 1 TO 23
    PRINT #2, i, chord(i), vel(i), Nslt(i), St(i)
    PRINT i, chord(i), vel(i), Nslt(i), St(i)
NEXT i
CLOSE #2
PRINT "Press any key to continue"
DO: LOOP WHILE INKEY$ = ""
'*****************************************************************
***
'Plot out the heat transfer solution for the blade using the PLOTT
subroutine
'This section drives the plotter for turbulence ON conditions.
ntot1% = 8    'This no. is the total no. of pressure side thermocou-
ples
ntot2% = 12    'This no. is to the total no. of suction side
thermocouples
ylab$ = "Temp. (C)": xlab$ = "x/c"
pltlab$ = "Temp. on turbine blade "
xmin! = 0!: xmax! = 1!: ymin! = 20: ymax! = 65
FOR i = 1 TO ntot1%
```

```
 ydat(i) = t2scan(i)
 xdat(i) = chord(i)
NEXT i
FOR i = ntot1% + 1 TO ntot2%    '?
 xdat(i) = chord(i)
 ydat(i) = 0
NEXT i
FOR i = ntot2% + 1 TO ntot1% + ntot2% + 3
 ydat(i) = t2scan(i - 4)
 xdat(i) = chord(i)
NEXT i
ntot% = ntot1% + ntot2% + 3
CALL PLOTT(xdat!(), ydat!(), xmin!, xmax!, ymin!, ymax!, xlab$,
ylab$, pltlab$, ntot%)
CASE "2": CLS : BEEP: LOCATE 7, 7
    PRINT "Turn off Blade Power before turning off the Fan"
    SLEEP 2: CLS : BEEP: LOCATE 7, 7
    PRINT "Turn off Blade Power before turning off the Fan"
    SLEEP 1: BEEP: SLEEP 1: BEEP: EXIT SUB
    EXIT DO
CASE ELSE: BEEP
END SELECT
LOOP
CALL IBWRT(dvm%, "RST")
END SUB
```

b Turbulence Data Reduction Program: TUBAT3.BAS

```
' Program to convert X-wire output voltages to u and v type
velocities.
' Also computes mean Uinf and beta values, and u' and v' for fft.
' Ver.final        L.Galassi 8-22-89   Modified by Capt Acree 9/90
Z$ = "99"   '<---------- This designates a horiz. plane in the test
section
CLS : LOCATE 5, 7: PRINT "TUBAT Program"
DEFINT I-N
pi! = 3.141593: dpr = 180 / pi
iflag% = 0
LOCATE 7, 7
COLOR 3, 0
INPUT "Normal configuration? ", yn$
IF yn$ = "y" THEN conf$ = "N" ELSE conf$ = "I"
INPUT "Get TU data files from disk: ", datadisk$
INPUT "Send output files to disk: ", dsk$
PRINT "This disk must have FFT and TURB directories."

' ---------------------------------------------- Read current
probe data
' The coefficient vectors b and b1 from the calibration program
' PROBECAL.MCD must be inverted for use in this program: this is
done as
' the vector values are retrieved from the P####_TF.dat file.

        PRINT "Probe data files list:": FILES "c:\lello\data\p*.dat"
        INPUT " Enter the serial#_Tf desired: ", serial$
        OPEN "C:\lello\data\p" + serial$ + ".dat" FOR INPUT AS #1
        INPUT #1, SN$, Z!, PL, c1!, b1!, a1!, c2!, b2!, a2!, k1!, k2!,
TF
        CLOSE #1
nn% = 2048 - 1
'nn% = 512 - 1
   DIM E1!(nn% + 2), E2!(nn% + 2), time!(nn% + 2), beta!(nn%),
Uinf(nn%)

4
PRINT "Probe data is :": PRINT SN$, TF, Z!, PL
PRINT a1!, b1!, c1!, k1!: PRINT a2!, b2!, c2!, k2!
PRINT "Note: the coefficient lists are in reverse order from the
MCAD list."
PRINT : PRINT "Press any key to continue.": DO: LOOP WHILE
INKEY$ = ""

b! = 45!
b! = (b! / 180) * pi!
dir$ = datadisk$ + ":\"
```

```
CLS : LOCATE 3, 7
PRINT "This is the current input file :"
LOCATE 5, 7: FILES dir$ + "tu*.dat"
LOCATE 15, 7
INPUT " Enter the 4-digit run/scan # : ", runscan$
file$ = "tu" + runscan$

CLS : LOCATE 7, 7
PRINT "Reading in data files from directory ", dir$
OPEN dir$ + file$ + ".dat" FOR INPUT AS #1

' ----------------------------------------- Read X,Y,Z etc from first
2 lines
        INPUT #1, X, Y, Z
        INPUT #1, PsiL, Sfa!, dummy
        PRINT "The Probe location (XYZ) and bisector angle was:"
        PRINT X, Y, Z, PsiL * dpr: SLEEP 2
FOR j = 0 TO nn%
        INPUT #1, time(j), E1(j), E2(j)
NEXT j: CLOSE #1
        PRINT "First/last time/voltage1/voltage2 are:"
        PRINT time(0), E1(0), E2(0)
        PRINT time(1), E1(1), E2(1)
        PRINT time(2), E1(2), E2(2): k = nn% - 1
        PRINT : PRINT time(k), E1(k), E2(k)
        PRINT time(nn%), E1(nn%), E2(nn%)
        PRINT "Press any key to continue.": DO: LOOP WHILE
INKEY$ = ""

alf! = pi! / 2 - b!

'---------------------------------- Perform computations for both
wires.

CLS : LOCATE 7, 7
PRINT "Computing velocities"
' ---------- compute U1eff and U2eff, store results back into E1()
and E2()

FOR i = 0 TO nn%                           ' master loop begins
here
        disc1 = b1! ^ 2 - 4! * a1! * (c1! - E1(i) ^ 2)
        disc2 = b2! ^ 2 - 4! * a2! * (c2! - E2(i) ^ 2)

        E1(i) = ((-b1! + SQR(disc1)) / (2! * a1!)) ^ 2
        E2(i) = ((-b2! + SQR(disc2)) / (2! * a2!)) ^ 2
' compute Beta and Uinf for each time step (normal and inverse
orientation)
```

```
 IF conf$ = "N" THEN
   discB = (k1! * E2(i) ^ 2 - E1(i) ^ 2) / (k2! * E1(i) ^ 2 - E2(i) ^
2)
         beta(i) = alf! - ATN(SQR(discB))
  ' assign a sign to the angle beta: if E1(i) > E2(i) then beta is
negative
   IF E2(i) > E1(i) THEN beta(i) = ABS(beta(i))
   IF E1(i) > E2(i) THEN beta(i) = -ABS(beta(i))
d! = E1(i) ^ 2 / ((COS(alf! + beta(i))) ^ 2 + k1! * (SIN(alf! +
beta(i))) ^ 2)
   Uinf(i) = SQR(d!)
'  PRINT USING "####.#"; SPC(25); i; beta(i) * dpr; Uinf(i)
 ELSE    ' ---------------------------- Inverse configuration
computations
   discBi = (k2! * E1(i) ^ 2 - E2(i) ^ 2) / (k1! * E2(i) ^ 2 - E1(i) ^
2)
         beta(i) = alf! - ATN(SQR(discBi))

'----------------------- assign a value to beta for the inverse
orientation
   IF E1(i) < E2(i) THEN beta(i) = -ABS(beta(i))
   IF E2(i) < E1(i) THEN beta(i) = ABS(beta(i))
d! = E1(i) ^ 2 / ((COS(alf! - beta(i))) ^ 2 + k1! * (SIN(alf! -
beta(i))) ^ 2)
   Uinf(i) = SQR(d!)
 END IF
'--- decompose velocities into u and v components and store in E1
and E2
delta! = 0                         ' For this study, delta! is
zero
         E1(i) = Uinf(i) * COS(beta(i) + delta!)
         E2(i) = Uinf(i) * SIN(-(beta(i) + delta!))
NEXT i                                          ' end of
master loop
' ------------------------------------------ Compute avg beta and
Uinf
bsum = 0: velsum = 0
FOR i = 0 TO nn%: velsum = velsum + Uinf(i): bsum = bsum +
beta(i): NEXT i
Uavg = velsum / (nn% + 1): bavg = bsum / (nn% + 1)
PRINT " Avg Uinf, Avg beta (deg) : ", Uavg, bavg * dpr
Psi = (PsiL - bavg) * dpr: PRINT "Psi (deg): ", Psi
' ------------------------------------------ Compute turbulence
levels
PRINT "Computing turbulence levels"
usum! = 0: vsum! = 0
```

```
FOR i = 0 TO nn%
        usum! = E1(i) + usum!: vsum! = ABS(E2(i)) + vsum!
NEXT i
umean! = usum! / (nn% + 1): vmean! = vsum! / (nn% + 1)
usum! = 0: vsum! = 0
FOR i = 0 TO nn%  '<<----------------------- Uinf and beta rede-
fined
Uinf(i) = (E1(i) - umean!)                          ' as u' and v'
usum! = Uinf(i) ^ 2 + usum!
beta(i) = (ABS(E2(i)) - vmean!)
vsum! = beta(i) ^ 2 + vsum!
NEXT i
tux! = SQR(usum! / (nn% + 1)) / umean!
tuy! = SQR(vsum! / (nn% + 1)) / umean!
'********************************************** Set up output to
data files
dirT$ = dsk$ + ":\TURB\"
dirF$ = dsk$ + ":\FFT\": file$ = runscan$
PRINT "Writing to data files on disk", dsk$,
OPEN dirT$ + file$ + ".vel" FOR OUTPUT AS #1
OPEN dirF$ + file$ + ".DAT" FOR OUTPUT AS #2
'********************************************  output to the FFT
data file
FOR i = 0 TO nn%
        PRINT #2, time(i), Uinf(i), beta(i)
NEXT i
CLOSE #2
'******************************************** output to normal
data storage
PRINT #1, "Turbulence Data File"; SPC(2); "VEL" + file$ + ".dat"
PRINT #1, ""
PRINT #1, "Turbulence generation grid location (x/b) ="; SPC(1);
"15.75"
PRINT #1, ""
PRINT #1, "Secondary injection pressure="; SPC(1); Sfa!; SPC(1);
"KPa"
PRINT #1, ""
PRINT #1, "U mean ="; SPC(1); umean!; SPC(1); "m/s"
PRINT #1, ""
PRINT #1, "V mean ="; SPC(1); vmean!; SPC(1); "m/s"
PRINT #1, "": Refs = umean! * .114 / 1.589E-05
PRINT #1, "Freestream Re No. ="; SPC(1); Refs
PRINT #1, ""
PRINT #1, "X - turbulence = "; SPC(1); tux! * 100!; SPC(1); "%"
PRINT #1, "Y - turbulence = "; SPC(1); tuy! * 100!; SPC(1); "%"
Turb = SQR((tux! ^ 2 + tuy! ^ 2) / 2) * 100!
PRINT #1, "Average turbulence = "; SPC(1); Turb; SPC(1); "%"
```

```
PRINT #1, ""
PRINT #1, TAB(2); "time (sec)"; TAB(19); "u (m/s)"; TAB(36); "v
(m/s)"
PRINT #1, "_______________________________________________"
PRINT #1, ""
FOR i = 0 TO nn% STEP 200
        PRINT #1, USING "###.#####"; time(i); SPC(8); E1(i); SPC(8);
E2(i)
NEXT i
PRINT #1, "                    End of Data": CLOSE #1
'------- This part saves the filename and mean velocities in a
header file
OPEN dsk$ + ":\M" + runscan$ FOR OUTPUT AS #1
PRINT #1, file$: PRINT #1, umean!: PRINT #1, vmean!
PRINT #1, X: PRINT #1, Y, : PRINT #1, Refs: PRINT #1, tux
PRINT #1, tuy: PRINT #1, Turb: PRINT #1, Uavg: PRINT #1, Psi:
CLOSE #1
' -------------------------------- Add mean data to Master Flow
file option
INPUT "Add mean flow values to the Z# master flow file on B: ?",
yn$
IF yn$ = "y" THEN
        PRINT "Current Z# is", Z$
        OPEN "B:Upsi-" + Z$ + ".dat" FOR APPEND AS #1
        PRINT #1, runscan$
        PRINT #1, X, Y, Uavg, Turb, Psi: CLOSE #1
END IF
INPUT "Print the Turb & t/u/v data? ", yn$
IF yn$ <> "y" THEN GOTO 100
'--------------------------- This prints part of the turbulence
data
'LPRINT CHR$(12)
LPRINT CHR$(27); "x"; CHR$(1)
OPEN "LPT1:" FOR OUTPUT AS #3
OPEN dirT$ + file$ + ".vel" FOR INPUT AS #1
DO UNTIL EOF(1)
        LINE INPUT #1, linebuffer$
        PRINT #3, SPC(13); linebuffer$
LOOP
CLOSE #3: CLOSE #1
LPRINT CHR$(12)
'********************************************** output to the
screen
```

```
100 CLS
PRINT "Output from turbulence data file", UCASE$(file$) + ".DAT"
PRINT
PRINT "U mean (m/s) ="; SPC(2); umean!; SPC(10); "V mean (m/s)
="; SPC(2); vmean!
PRINT "X turbulence (%) ="; SPC(2); tux! * 100!
PRINT "Y turbulence (%) ="; SPC(2); tuy! * 100!
PRINT "Re No. = "; SPC(2); umean! * .114 / 1.589E-05
PRINT "Consolidated turbulence (%) ="; SPC(2); SQR((tux! ^ 2 + tuy!
^ 2) / 2) * 100
PRINT

PRINT "time(sec)"; SPACE$(9); "u (m/s)"; SPC(8); "v (m/s)"
PRINT
"____________________________________________________________________"

FOR i = 1 TO nn% STEP 200
        PRINT USING "##.#####"; time(i); SPC(8); E1(i); SPC(8); E2(i)
NEXT i

SLEEP 10: LOCATE 24, 7: INPUT "Crunch another file (same probe)?
", yn$
IF yn$ = "y" THEN GOTO 4
PRINT "Normal Program Termination": SLEEP 1
END
```

c Fast Fourier Transform Program: FFTBAT3.BAS

```
DECLARE SUB GetData (datflag%, runscan$)
DECLARE SUB RealFT (dat() AS SINGLE, n%, ISIGN%)
DECLARE SUB Fourl (dat() AS SINGLE, NN%, ISIGN%)

        DEFINT I-N

        DIM X(4096) AS SINGLE, Y(4096) AS SINGLE, En(4096) AS
SINGLE
        CLS : LOCATE 7, 7
        COLOR 3, 0
        PRINT "Entering FFT program for data reduction"
        PRINT "The output disk must have FFT and SPECTRUM
directories."
        INPUT "Output goes to disk: ", dsk$
        SLEEP 5: CLS : LOCATE 7, 7
        datflag% = 1     ' --------------   Indicates u data, vice v
data
INPUT "Get run/scan data from disk: ", datadsk$
4 FILES datadsk$ + ":\M*"
INPUT "Enter 4-digit run/scan # for processing. ", runscan$
OPEN datadsk$ + ":\M" + runscan$ FOR INPUT AS #1
        INPUT #1, runscan$: INPUT #1, umean#: INPUT #1, vmean#
        INPUT #1, X: INPUT #1, Y
        CLOSE #1
        PRINT "Run/scan is ", SPC(1); , runscan$
        LPRINT CHR$(10)
        CLOSE #1
5   CALL GetData(datflag%, runscan$)
        dt = .00002
        xpts = npts
        real2 = 2
        nexp = LOG(xpts) / LOG(real2)
'---------------------------------------- FFT performed for 2*n
data points
        n = 2 ^ (nexp - 1)
' ------------------------------------ Perform the forward Four-
ier transform
        CLS : LOCATE 10, 1
        PRINT "Beginning FFT for 2*", n, " points..."

        CALL RealFT(Y(), n, 1)

        CLS : LOCATE 9, 7
        PRINT "Computing scales"
```

```
        pi# = 3.141592654#
        df = 2 * n * dt
        dw# = 1# / df
        FOR i = 3 TO n + 1
            j = 2 * (i - 2) + 1
            X(i - 2) = (i - 2) / df
            Y(i - 2) = SQR(Y(j) * Y(j) + Y(j + 1) * Y(j + 1)) / (2 *
n)
            En(i - 2) = ((Y(i - 2) ^ 2) * 2#) / dw#
        NEXT i
' ------------------------------------------- Summation of
integrand
        freqmax% = 19000
        freqmax% = CINT(freqmax% / dw#)
        sum# = 0#
        FOR i = 3 TO freqmax%
                sum# = (i ^ 2) * En(i - 2) + sum#
        NEXT i
'  ---------------------------------------------- Store data
----------
dir$ = dsk$ + ":\FFT\" + runscan$
        CLS : LOCATE 9, 7
        PRINT "Writing FFT data to :", dir$ + "-" + ans1$ + ".dat"
        OPEN dir$ + "-" + ans1$ + ".dat" FOR OUTPUT AS #1
        FOR i = 3 TO n + 1
                PRINT #1, X(i - 2), Y(i - 2)
        NEXT i
        CLOSE #1
          dirs$ = dsk$ + ":\spectrum\" + runscan$
CLS : LOCATE 7, 7
OPEN dirs$ + "-" + ans1$ + "S" + ".dat" FOR OUTPUT AS #2
        LOCATE 7, 7
PRINT "Writing Grapher file to :", dsk$ + ":\" + runscan$ + ans1$
+ "S.dat"
        FOR i = 3 TO 300
                PRINT #2, X(i - 2), En(i - 2)
        NEXT i
        FOR i = 301 TO 502 STEP 3
                PRINT #2, X(i - 2), En(i - 2)
        NEXT i
        FOR i = 503 TO freqmax% STEP 6
                PRINT #2, X(i - 2), En(i - 2)
        NEXT i
        CLOSE #2
```

```
        IF datflag% = 1 THEN
                mean# = umean#
                factor# = up2m#
        ELSE
                mean# = vmean#
                factor# = vp2m#
        END IF
' Compute the microscale of turbulence
        lmbdaf# = SQR(1# / (sum# * 2# * pi# ^ 2) / (mean# ^ 2 *
factor#))
' Compute the integral scale of turbulence

        En0# = 0#
        FOR i = 1 TO 40
                En0# = En(i) / 40# + En0#
        NEXT i

        integ# = (mean# / (4# * factor#)) * En0#
        CLS : LOCATE 7, 7
PRINT ans1$ + "-" + "turbulence microscale ="; SPC(1); lmbdaf#;
SPC(1); "m"
        LOCATE 9, 7
PRINT ans1$ + "-" + "turbulence integral scale ="; SPC(1); integ#;
SPC(1); "m"
        SLEEP 5
        PRINT "Writing scales to ", SPC(1); , dsk$ + ":\scales"

        OPEN dsk$ + ":\scales" FOR APPEND AS #3
        PRINT #3, runscan$, X, Y, integ#, lmbdaf#
        CLOSE #3
' ---------------------------------- scales printout
----------
        LPRINT CHR$(27); "x"; CHR$(1)
        OPEN "LPT1:" FOR OUTPUT AS #3
        PRINT #3, SPC(4); runscan$
        PRINT #3, SPC(4); "If" + ans1$ + "  ="; SPC(1); integ#;
SPC(4); "Lf" + ans1$ + " = "; SPC(1); lmbdaf#
        CLOSE #3
' ---------------------------------------- Return and do the v
data
        IF datflag% = 1 THEN
                datflag% = 2
                GOTO 5
        END IF
                LOCATE 7, 7: INPUT "Restart (Y/n)?", yn$
```

```
                IF yn$ <> "n" THEN GOTO 4
        PRINT "Normal Termination of FFT Program"
END

    SUB Four1 (dat() AS SINGLE, NN, ISIGN)
      DIM WR AS DOUBLE, WI AS DOUBLE, WPR AS DOUBLE, WPI AS
DOUBLE
      DIM WTEMP AS DOUBLE, THETA AS DOUBLE
      'DIM dat(4096) AS SINGLE
      n = 2 * NN
      j = 1
      FOR i = 1 TO n STEP 2
        IF j > i THEN
          TEMPR = dat(j)
          TEMPI = dat(j + 1)
          dat(j) = dat(i)
          dat(j + 1) = dat(i + 1)
          dat(i) = TEMPR
          dat(i + 1) = TEMPI
        END IF
        m = n / 2
1       IF ((m > 2) AND (j > m)) THEN
          j = j - m
          m = m / 2
        GOTO 1
        END IF
        j = j + m
11    NEXT i
      MMAX = 2
2     IF n > MMAX THEN
        ISTEP = 2 * MMAX
        THETA = 6.28318530717959# / (ISIGN * MMAX)
        WPR = -2# * SIN(.5# * THETA) ^ 2
        WPI = SIN(THETA)
        WR = 1#
        WI = 0#
        FOR m = 1 TO MMAX STEP 2
          FOR i = m TO n STEP ISTEP
            j = i + MMAX
            TEMPR = WR * dat(j) - WI * dat(j + 1)
            TEMPI = WR * dat(j + 1) + WI * dat(j)
            dat(j) = dat(i) - TEMPR
            dat(j + 1) = dat(i + 1) - TEMPI
            dat(i) = dat(i) + TEMPR
            dat(i + 1) = dat(i + 1) + TEMPI
          NEXT i
          WTEMP = WR
          WR = WR * WPR - WI * WPI + WR
          WI = WI * WPR + WTEMP * WPI + WI
```

```
      NEXT m
      MMAX = ISTEP
    GOTO 2
    END IF
END SUB
    SUB GetData (datflag%, runscan$)
        SHARED file$, X() AS SINGLE, Y() AS SINGLE, npts, ansl$,
up2m#, vp2m#
        CLS : COLOR 3, 0: LOCATE 7, 7
        dir$ = "A:\fft\"
        file$ = runscan$
        OPEN dir$ + file$ + ".dat" FOR INPUT AS #1

        npts = 2048

        IF datflag% = 1 THEN
                ansl$ = "u"
        ELSE
                ansl$ = "v"
        END IF
        CLS : LOCATE 9, 7: PRINT " Reading in data from :", dir$ +
file$

        IF ansl$ = "u" THEN
                usum# = 0#
                FOR i = 1 TO npts
                    INPUT #1, X(i), Y(i), dummy
                    usum# = Y(i) ^ 2 + usum#
                NEXT i
                up2m# = usum# / npts
        ELSE
                vsum# = 0#
                FOR i = 1 TO npts
                    INPUT #1, X(i), dummy, Y(i)
                    vsum# = Y(i) ^ 2 + vsum#
                NEXT i
                vp2m# = vsum# / npts
        END IF

        CLOSE #1
```

```
        CLS : LOCATE 7, 7
        IF datflag% = 2 THEN
        PRINT "u'^2 mean (m/s) = ", up2m#
        LOCATE 9, 7
        PRINT "v'^2 mean (m/s) =", vp2m#
        SLEEP 3
        END IF
    END SUB
SUB RealFT (dat() AS SINGLE, n, ISIGN)
      DIM WR AS DOUBLE, WI AS DOUBLE, WPR AS DOUBLE, WPI AS
DOUBLE
      DIM WTEMP AS DOUBLE, THETA AS DOUBLE
      'DIM dat(4096) AS SINGLE
      THETA = 6.28318530717959# / 2# / n
      C1 = .5
      IF ISIGN = 1 THEN
        C2 = -.5
        CALL Four1(dat(), n, 1)
      ELSE
        C2 = .5
        THETA = -THETA
      END IF
      WPR = -2# * SIN(.5# * THETA) ^ 2
      WPI = SIN(THETA)
      WR = 1# + WPR
      WI = WPI
      N2P3 = 2 * n + 3
      FOR i = 2 TO n / 2 + 1
        I1 = 2 * i - 1
        I2 = I1 + 1
        I3 = N2P3 - I2
        I4 = I3 + 1
        WRS = WR
        WIS = WI
        H1R = C1 * (dat(I1) + dat(I3))
        H1I = C1 * (dat(I2) - dat(I4))
        H2R = -C2 * (dat(I2) + dat(I4))
        H2I = C2 * (dat(I1) - dat(I3))
        dat(I1) = H1R + WRS * H2R - WIS * H2I
        dat(I2) = H1I + WRS * H2I + WIS * H2R
        dat(I3) = H1R - WRS * H2R + WIS * H2I
        dat(I4) = -H1I + WRS * H2I + WIS * H2R
        WTEMP = WR
        WR = WR * WPR - WI * WPI + WR
        WI = WI * WPR + WTEMP * WPI + WI
      NEXT i
```

```
    IF ISIGN = 1 THEN
      H1R = dat(1)
      dat(1) = H1R + dat(2)
      dat(2) = H1R - dat(2)
    ELSE
      H1R = dat(1)
      dat(1) = C1 * (H1R + dat(2))
      dat(2) = C1 * (H1R - dat(2))
      CALL Four1(dat(), n, -1)
    END IF
END SUB
```

2 Procedures

a General

Verify that the high-speed cable is connected between FET module 3 and the high-speed voltmeter. Turn on the HP3852A and let it warm up for an hour prior to taking thermal data. Turn on all the remaining equipment: 10 volt DC power supply, Scanivalve controller and indicator, IFA-100, oscilloscope, 100 amp DC power supply, digital multimeter, Zenith computer and printer. Using the multimeter, verify that the small power supply is providing 10.0 volts.

Clean off small insects impacted on the pressure surfaces of the blades. Select a probe calibrated for the current room temperature and above - the room temperature will rise about 3 degrees during tunnel warmup, but should stabilize. Clean the probe in rubbing alcohol. Place index arm 2 in a vise, then insert the probe into the mount. Rotate the mount to line up the short support posts with the centerline marking of arm 2, then adjust the protractor clamp to line up the 0/360 mark with the probe bisector. Tighten the clamp, then remove the probe.

Place disk 1 over the mount held by index arm 2, then reattach the probe. Adjust and measure the depth of the sensor wires, and record. Release the vise, and lift the assembly over the test section. Fit index arm 1 over the mounting post, and lower the index arm and disc 1 into place in the eccentric cutout

on disc 2. Position the probe and the grid tubes for the test.

Turn on the tunnel fan, then apply 15 amps to blade #2. Allow 30 minutes for the interior to reach steady state temperature. The highest temperature occurs at tap #10; do not let this exceed 60 C, or the urethane foam will begin to produce gases that will push the foil away from the blade. Set up the IFA-100 for the probe, then set both channels to RUN.

To begin the test, perform a pressure survey first, followed by a temperature survey. Record the amperage on the DC ammeter, and record the voltage drop across the blade foil. Changes in the resistance of the foil can be tracked to verify that current is not leaking through the blade interior.

After the test, set both IFA-100 channels to STANDBY, and turn off the DC current to the blade foil. After the blade temperature has dropped, the tunnel fan can be turned off.

b Data Reduction Path

The data path is represented in Figure D.1. Following conversion to velocities and velocity fluctuations in the TUBAT program, the velocity fluctuation file is reduced in the FFTBAT program to obtain the turbulence scale parameters and frequency spectrum files. Five frequency runs fit on a 1.2 MB floppy disk after reduction by TUBAT.

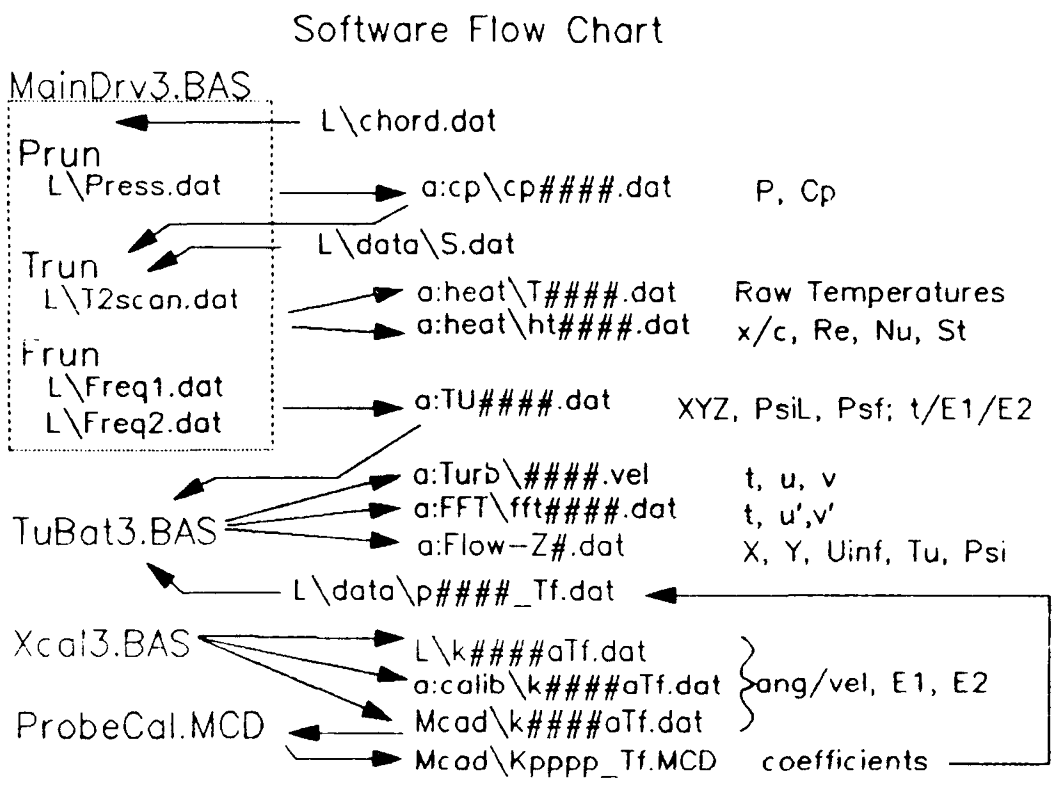


Figure D.1 Data Reduction Path

E. Thermal Data

1 Temperature Profiles

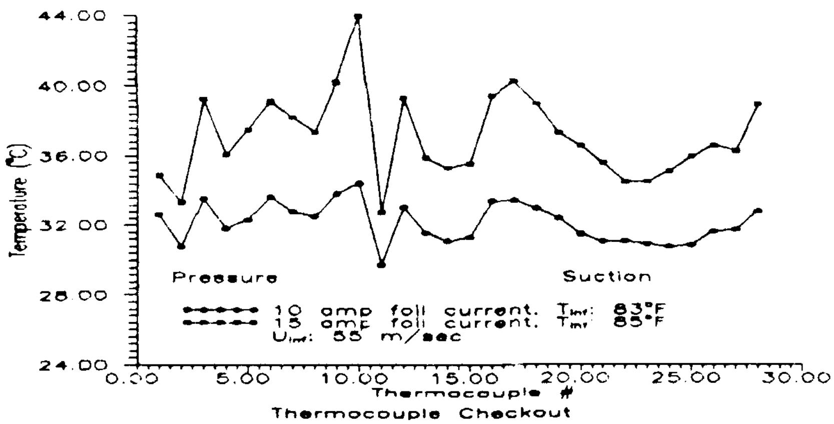


Figure E.1 Temperature Profiles

Data from thermocouples 9 through 12 were not used, due to no heating (#11) or unknown current density (#9, 10, & 12). Figure E.1 shows the temperature profiles for two current levels, no grid.

Thermocouples 9, 10, and 12 show higher temperatures due to higher current per unit surface area in their location. This was due to the copper bus bar not extending across the foil width, giving nonuniform current across the foil. Transition from laminar to turbulent flow is evident on the suction surface at thermocouple 17.

Figure E.2 shows three successive temperature samples at t=30 minutes after power application to the foil, and shows that the blade interior had reached steady state temperature.

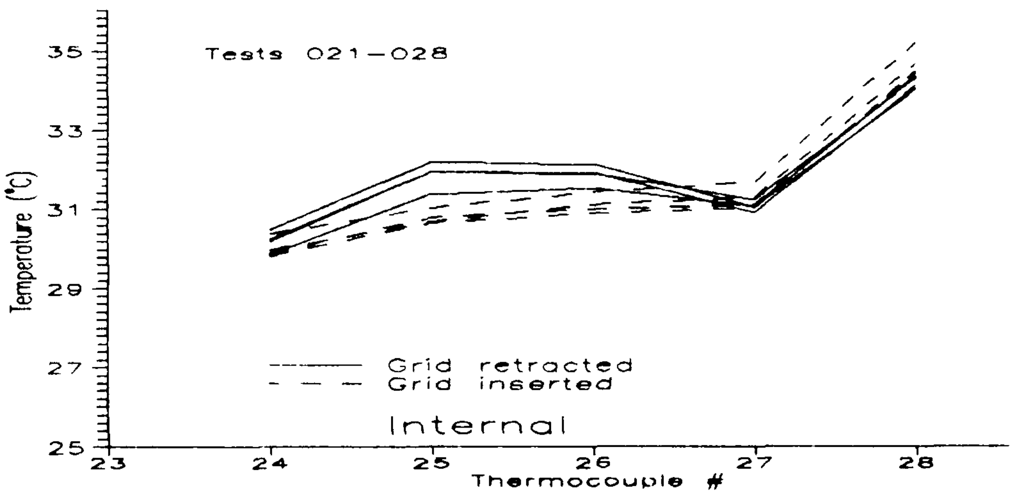


Figure E.2 Internal Temperature Profile

2 Heat Transfer

a *Qualitative Error Analysis*

With the jet-grid inserted into the primary flow, the possiblity of overstatement of Reynolds number arose; the local Stanton number is derived from local Reynolds number (a function of local velocity), and is now suspect. The local velocity is derived from the C_p values with the relation

$$v_l = \sqrt{U_\infty^2 \cdot |1 - C_{p,l}|}$$

In Section V, it was pointed out that the condition causing the increase in angle of incidence would also cause a low value of q (due to the location of the pitot-static tube). In the above relation, however, q appears in the form of $U_\infty \propto \sqrt{q}$, and also in the form of C_p, so that the net result is the error raised to the negative one-half power. The understatement of q results in a smaller overstatement of local velocity and hence Reynolds number. Stanton number is derived by use of the relation

$$St_x = \frac{N_x}{Pr \cdot Re_x}$$

The slightly overstated Reynolds number thus causes a slightly understated Stanton number. It should be remembered that the error was consistently applied in the computation, so that trends in Stanton number along the blade surface are valid

The Nusselt number, however, is derived independently of local Reynolds number, with the exception of taps 1 and 2, where

the blunt nose stagnation point relation was employed (Equation 2.1). This relation uses the square root of a radius-based Reynolds number, which would still be slightly overstated, since it was derived from pressure coefficients. The error appears to the negative one-fourth power for Nusselt, and to the positive one fourth power in Stanton number at taps 1 and 2. For all other blade locations, the Nusselt numbers are completely free of the low q error.

In summary, the Stanton number is slightly understated everywhere, but less so on the leading edge. Nusselt is slightly overstated on the leading edge, but correct at all other locations.

b Results

The results indicate little of interest on the suction side, but the pressure side heat transfer confirms the appearance of a flow anomaly in the same location as the separation bubble. Increased heat transfer in this region does not follow increasing secondary injection uniformly; rather, it follows the erratic pressure coefficient behavior noted earlier, and is therefore attributed not to changes in turbulence, but to erratic changes in angle of incidence.

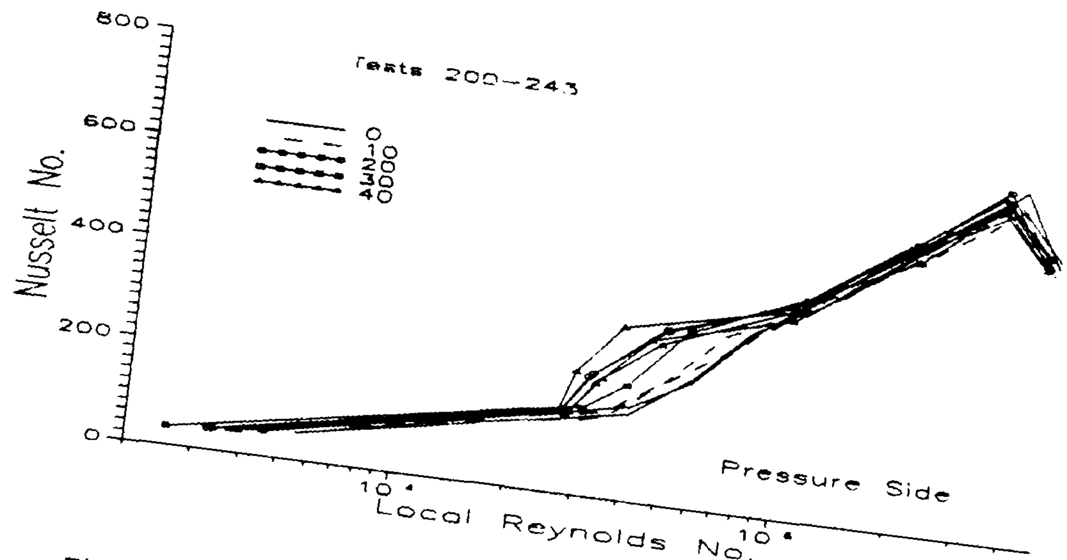


Figure E.4 Nusselt No. vs Reynolds No. - Pressure Side

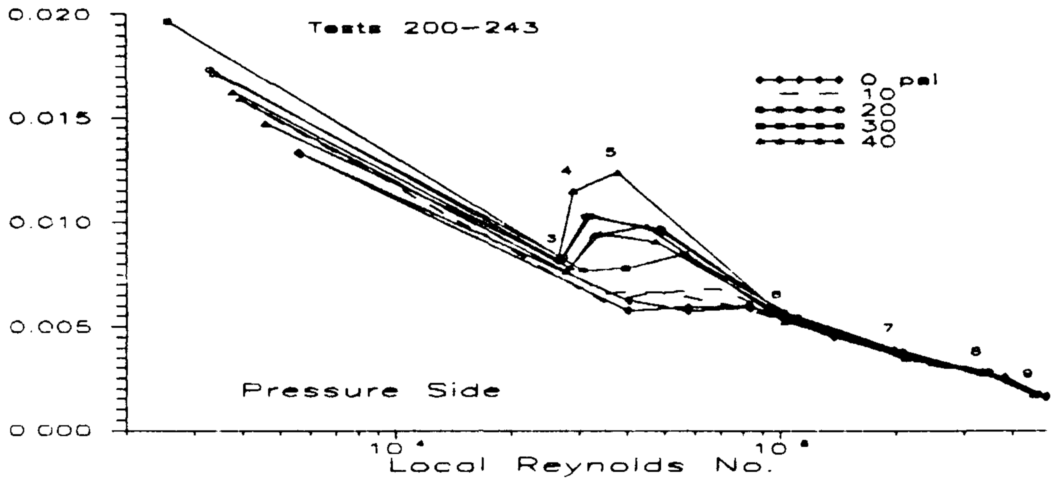


Figure E.5 Stanton No. vs Reynolds No. - Pressure Side

F. Equipment List

The Turbine Cascade Test Facility was designed in part by Lt Col Paul King, and was built at the Air Force Academy. The equipment listed in table F.1 was used at Building 19, the AFIT five-foot wind tunnel facility, at Wright-Patterson AFB. Hewlett-Packard is abbreviated as HP.

Table F.1 Equipment List

Item	Model	Serial #
Zenith PC	386/387 installed	704AH0041
Scanivalve	2 psi module	TS2 36
Display unit	n/a	832 BINY
Controller	2P/S2-S6	1745
HP Multimeter	3438A	1717A-07469
Weston Electric Ammeter	430	26230
HP 2 Amp Power Supply	6236B	2140A-13942
HP 100 Amp Power Supply	6456B	2410A-02176
BK Oscilloscope		1570A
TSi IFA-100		337C
HP Data Acquisition Unit	3852A	n/a
Neff Amplifier	119	LH5469

G. Test Section Pressure Data

Total and static pressure were measured with a pitot-static tube inserted between the grid location and the cascade entrance plane. The depth was adjusted to approximately mid span. The static ports of the tube were checked with an oil manometer prior to use in the tunnel. The pitot-static pressures were measured last, after proceeding in number order around the blade surface.

Figure G.1 shows the effect of grid insertion and secondary flow on the total and static pressures prior to cascade entry. All pressures are gauge, referenced to atmospheric. The insertion of the grid caused a marked total pressure loss, and a small static pressure drop. Static pressure showed no dependence on secondary flow. Secondary flow did not significantly alter the total pressure beyond a small drop (less than 0.5 kPa).

This second drop in total pressure was attributed to the blocking of the flow by the formation and lengthening of the jets as they emerge from the grid tubes. Near the tube orifices, the jets appear to the oncoming flow as cylinders; farther from the tube, these cylinders widen into plumes and begin to acquire downstream velocity components. As the secondary pressure increases, the initial velocity of the jets increase, causing the jets to retain their cylindrical shape until well away from the orifice. Eventually, the jet plumes elongate until they are in the wake of plumes emerging from the upstream adjacent tube. At this point, the blockage of the primary flow is in the form of a grid;

vertical tubes and horizontal jets. The total pressure loss does not increase beyond this point, regardless of increases in secondary flow velocity, since the area of the grid blocking the primary flow does not increase.

Vita

Captain James Lance Acree [redacted] and graduated from St. Johns Country Day School in 1976. He attended Auburn University in Auburn, Alabama, and graduated in 1980 with a Bachelor of Mechanical Engineering (with honor). He completed Undergraduate Pilot Training at Vance AFB, Oklahoma, in 1982. From 1982 to 1989 he was assigned to C-130 units in Alaska and Arkansas, and served as instructor pilot in the DoD C-130 Formal School at Little Rock AFB until he entered the AFIT School of Engineering. In June 1990, the University of Arkansas awarded him the Master of Science in Engineering for completing their Engineering Management program. Captain Acree is married and has three children.

[redacted]

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13. ABSTRACT (*Maximum 200 words*)

This study examined the behavior of turbulence parameters in the passage of a linear turbine cascade. Turbulence was generated upstream of the cascade by means of a jet-grid device inserted into the flow. Local velocity was measured in two components. Velocity fluctoation and turbulence integral scale adn turbulence microscale were determined. Turbulent kinetic energy dissipation was computed. Results indicate that the jet-grid changed the angle of incidence on the instrumented blade. The turbulence intensity adn integral scale remained fairly constant with increasing grid njection, but the micro-sclae increased. In the passage, velocity fluctuation and microscale are inversely related. ' With 6% freesteram turbulence intensity, the passage center flow is influenced first by events near the suction surface, then by events near the pressure surface. The primary vehicle for cross-stream diffusion of turbulent kinetic energy is increased cross-stream velocity fluctuation.

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